# 3.—PERMIAN SUCCESSION AND STRUCTURE IN THE NORTHERN PART OF THE IRWIN BASIN, WESTERN AUSTRALIA

by

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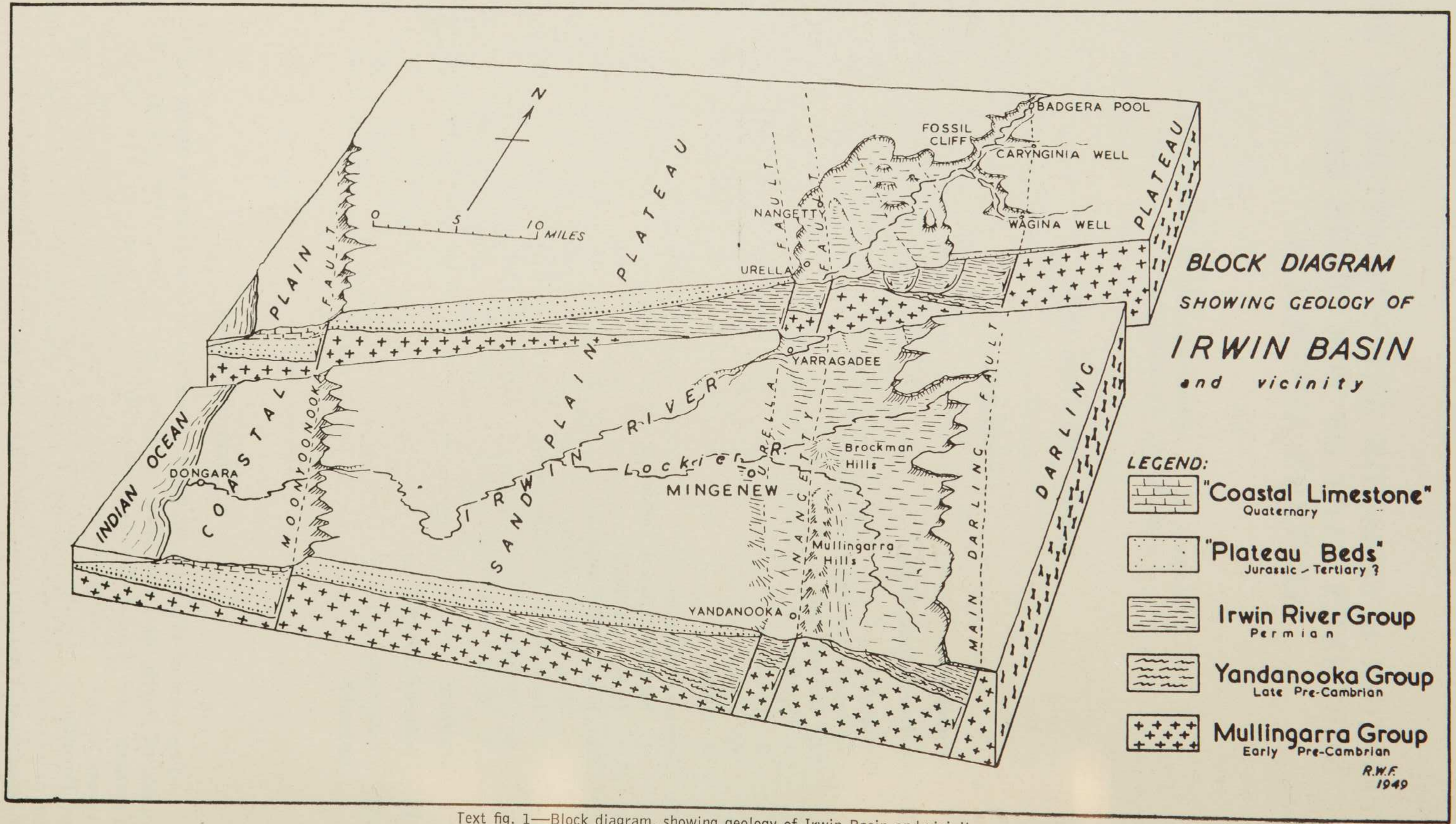
CONTENTS.

## I.—INTRODUCTION.

The part of Western Australia described in this paper is about 250 miles north of Perth, and has been mentioned in various papers dealing with the Permian and Carboniferous succession in the Southern Hemisphere. It covers an area of about 75 square miles and is, essentially, a varied sequence of Permian sediments of not less than 3,500 and probably about 4,000 feet in thickness. Structurally the beds lie tilted gently on a heavily faulted basement of Pre-Cambrian, and are further faulted in themselves along numerous minor lines (*see* text fig. 1). No folding is recognised.



Text fig. 1—Block diagram, showing geology of Irwin Basin and vicinity.

The mapped area lies in the northern part of a physiographic basin, intersected by the Irwin River, and surrounded by undulating plateau lands standing about 1,000 feet above sea-level. The thin sandstone beds of the plateau, resting unconformably on the peneplaned Permian, have been classed variously as Jurassic and Tertiary: that problem will be discussed in another paper.

This paper presents the results of the geological mapping done by many parties of students of the University of Western Australia during the last 25 years, notable years being 1934–37, 1939 and 1948–49. This work was directed and co-ordinated by the senior author (E. de C. C.). The final map was prepared by the junior author (R. W. F.) largely from air photographs based on the control of the military survey (1 in. to mile) of 1942, and information supplied by the Lands and Surveys Department, to which have been added details from a very large number of chain and compass traverses by students, supplemented by work with plane table and telescopic alidade. It should be noted, however, that the photographs do not cover the area east of a line from Fossil Cliff to Holmwood. Some reference to results obtained was made by Clarke (1937)* and Teichert (1939, 1941, 1947).

Unpublished official records were made available to us by the Lands and Surveys Department and the Geological Survey of Western Australia. Mr. J. Butcher, of Nangetty Station, the Mungedar Pastoral Co., and Messrs. J. J. R., and W. Holmes, of Holmwood Station, not only allowed the various parties of students free access to their properties, but also took a very keen and practical interest in the progress of the work and the welfare of the students.

It is not possible to mention by name the many students whose work has formed the basis of this contribution which has covered so many years. Thanks are due to the Senate of the University of Western Australia for the award of a Hackett Studentship to one of us (K.L.P.) which made possible her share in this work.

Work in 1939 was in part financed from the Commonwealth Research Grant to the University of Western Australia. Additional assistance from this source was received in 1949.

## II.—PREVIOUS INVESTIGATIONS.

On 9th September, 1846, the Gregorys (A. C. and F. T. Gregory, 1884, p. 8) discovered two seams of coal in the bed of the Irwin River—the first record of coal in Western Australia. To quote the original words: "We therefore entered the bed of the river to examine it, and found two seams of coal—one five feet thick and the other about six feet thick—between beds of sandstone and shale. Having pitched the tent and tethered the horses, we commenced to collect specimens of the various strata, and succeeded in cutting out five or six hundredweight of coal with the tomahawk, and in a short time had the satisfaction of seeing the first fire of Western Australian coal burning cheerfully in front of the camp, this being the first discovery of coal in the western part of the Continent."

Next year, or early in 1848, Ferdinand von Sommer was appointed to "investigate and report on certain coal deposits in the colony." He stated that he had traced the Irwin River Coalfield from the heads of the Irwin River to those of the Moore, a distance of about 160 miles, and he described the coal

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* In this publication, reference was made to a manuscript by K. L. Prendergast and N. Luck, which was never published, but served as the starting point for the present paper.

seams as dipping to the N.N.W. " under an angle of 72°." As those in the North and South Branches of the Irwin have a dip of 10° to the east, they cannot be identical with von Sommer's seams. He may, however, have found outcrops, now perhaps obscured, near the main fault in Caryngina Gully where north-west dips of 70° are recorded in Coal Measure facies.

From then onwards, many reports, most of them short and on special features, have appeared. Reference to some of these will be made later, but no summary would be adequate without mention of the following :—

A preliminary sketch-map of the area was made by Maitland in 1903 and his first impression of the structure was published. At the same time he noted Etheridge's report on the " Carboniferous " *Dielasma-Aviculopecten* fauna from one mile east of Mingenew, discovered by Simpson (Maitland, 1904).

C. F. V. Jackson made an examination of the district in August, 1904. No record of his work can be found, but he collected the first specimens of the cephalopod *Metalegoceras jacksoni*, originally described as a *Gastrioceras*, from a spot about 24 chains east of Mesa No. 3. R. Etheridge (1907, p. 26) expressed the opinion that the facies of the fossils collected by Jackson " is eminently that of the Carboniferous as distinguished from the higher Permo-Carboniferous."

The geologist who first mapped the whole Irwin River district was W. D. Campbell, of the State Geological Survey (1910). He considered that the sandstones, limestones and shales which Nicolay (1886) had noted underlying the coal seams on the east side of the broad valley of the Irwin River, outcrop also on the other side of the valley, are about the middle of the series, are underlain by tillites, and that the whole series is folded into a broad anticline whose axis runs west of north.

The presence of boulder beds here had already been noticed by Maitland in 1897, but at first he was not positive that they were glacial ; true tillites were confirmed in the Gascoyne area to the north in 1900 and Campbell found abundant striated boulders in the Irwin area in 1908 (Maitland, 1912).

Campbell's was a very notable contribution to the knowledge of Australian geology. Although he was required to report on about 2,000 square miles of country which is even now difficult to examine geologically and was very much more so under the conditions thirty years ago, yet his general conclusions regarding the stratigraphy are still accepted, and our admiration and envy are roused by his acute observations and thorough collecting in the 75 square miles with which we are concerned and in which he could only have spent a small fraction of the time represented by the united efforts of our parties.

In 1924, Woolnough and Somerville carried out a rapid, though more detailed survey of the northern part of the Irwin Basin, dividing the sequence into a number of individual formations, most of which we have been able to recognise. They also identified the essentially block-faulted nature of the regional structure, but, encouraged by a new discovery of " *Gastrioceras* " beds on the west side of the basin, followed Campbell in interpreting the main structure of the basin as anticlinal.

The area has been referred to since then in numerous publications, most of which have dealt with brief reconnaissances, aspects of the palaeontology (*see* below, under " Permian Succession "), or with problems of regional correlation (which will also be referred to under the appropriate headings).

## III.—TOPOGRAPHY.

### 1. General Description of Area.

The average annual rainfall of the district is about 15 inches, and practically all the rain falls in winter. The natural vegetation was probably a moderately dense growth of " jam " (*Acacia acuminata*), " reminder " (*Hakea recurva*), on the higher ground and river terraces, " sheoak " (*Casuarina glauca*) and " river gums " (*Eucalyptus rostrata*) in the watercourses. Clearing and over-stocking have led to the destruction of most of the larger plants with resultant rapid soil erosion. During the winter and spring, however, the country is covered with a luxuriant growth of annuals, some native and some introduced, and is acknowledged to be some of the best pastoral country in the State, stock thriving on the dry herbage, seeds and shrubs during the dry season if a sufficiency of water is available. The chief source of water supply is from excavated earthen tanks (" dams "), springs being of very minor importance. Bores for water have only been successful near the extreme margins of the basin, that is in aquifers lying above the saline formations.

The area with which this paper deals is really the middle portion of the valley of the Irwin River. The Irwin has a total length of about 60 miles and rises on the Great Plateau of Western Australia at a height of about 1,000 feet above sea level. Its upper part, known as the North Irwin, flows, in general, south-west for about 35 miles, and passes, without deviation, over the junction between the Pre-Cambrian and the Permian rocks. The upper part of the course of the North Irwin in the Permian rocks is in a fairly narrow gorge, bounded by cliffs about 100 feet high (*see* text figs. 11 and 12). The gorge ends where the river is met by a large tributary (the South Irwin) which comes in from the south-east. Below this junction, which will be referred to as "the Junction " in this paper, the cliffs which bound the gorge recede from the river, which now flows in a series of meanders through a valley eight or more miles wide, bounded everywhere by low cliffs, or breakaways (*see* text figs. 2, 3 and 4), which are continuous with the more imposing cliffs of the upper gorge.

South of the area with which we are concerned, the Irwin, without deviating from its general trend, is joined by an almost equally long river—the Lockier. A short distance below the junction the river turns and flows west for about 20 miles to enter the sea at Dongara. Jutson (1934, pp. 179–80) comments on the unsolved physiographic problems presented by the Irwin River.

The area over which we worked—too restricted to render possible any general explanation for the features described above—consists of the broad shallow valley of the Irwin and of the tableland in which this valley lies.

The brief physiographic notes which follow may be arranged under the headings : Watercourses, Springs, Lowlands, Plateaux, and Hills.

### 2. Watercourses.

The Irwin River resembles most of the rivers of Western Australia in that it, and its tributaries, are intermittent, flowing only for a short time after heavy rains, when it carries relatively large amounts of silt and sand towards the sea (Carroll and Clarke, 1941, p. 174).

The principal tributary of the North Irwin is known as Caryngintia Creek, and a small one passing near Bigarra ("Dog Hole") Spring is named after that spring. In the South Irwin there are only very small tributaries, of which we have named for convenience: Research Creek, Monday Creek, Trio Creek. Below the Irwin Junction, only the largest tributaries have been named: Eagle Creek, Gnoolowa Creek, Cat Creek, Mullewa Creek (with Tillite Creek joining it), Beckett's Creek and Nangetty Creek. Being dry for so much of the year, many of these watercourses are often more appropriately referred to as "gullies."

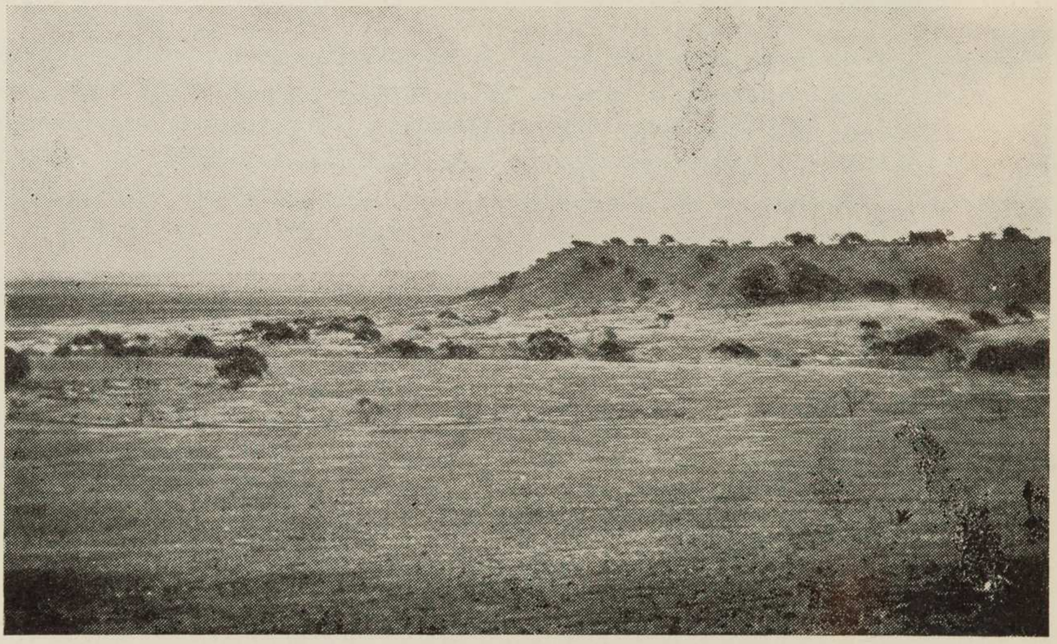
### 3. Springs.

The perennial springs, which occur at different geological horizons, are inconspicuous though some are of practical importance. They are of three types :—

(a) Those in the Permian, from various horizons, particularly in the Coal Measures and at the base of the Fossil Cliff Formation (*e.g.*, Warraga Spring, at Fossil Cliff). These are almost all saline and gypseous, being generally quite unfit for stock or human consumption.

(b) Those issuing from the base of the plateau beds, occurring at various points along the breakaways which border the Irwin River valley. The "Dog Hole" (Bigarra Spring) in the North Irwin is an example of this second type ; another and larger one lies a mile WNW of Nangetty Homestead and several smaller springs occur along the sides of Mesas 3 and 4. It was near such a spring north of Coal Seam Homestead that we found some native land snails, corresponding closely to *Sinumelon vagente* Iredale. Near other soaks beneath the breakaways is sometimes found a small variety of *Bothriembryon.*

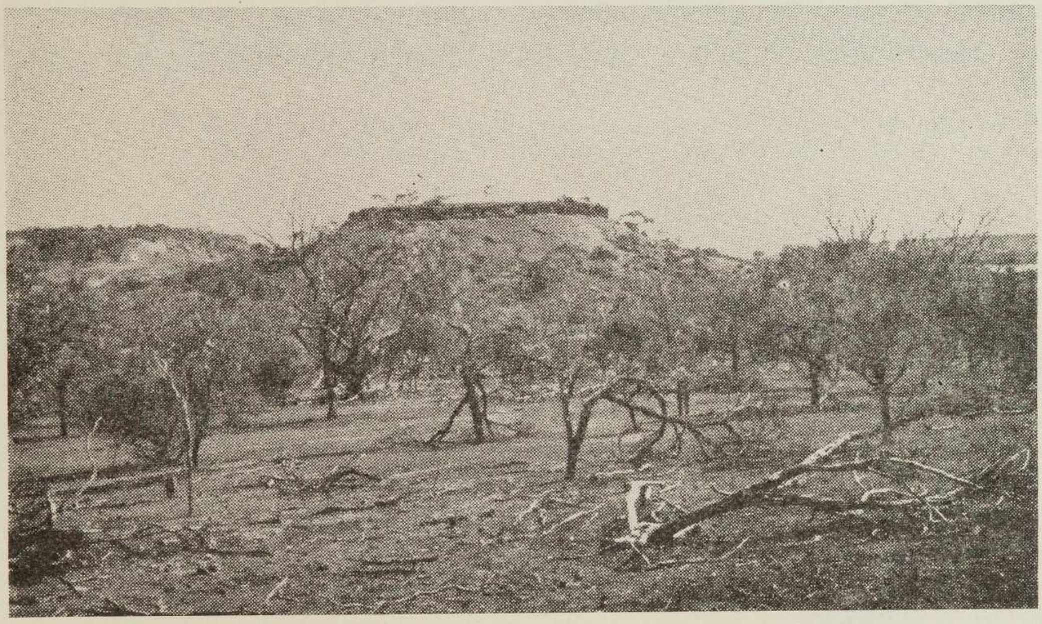
(c) A third type, issuing, it has been suggested, along a fault (Woolnough and Somerville, 1924, p.105), lies almost outside the area dealt with in this paper, but is mentioned briefly in our discussion on Structure (Section V.).



Text fig. 2—Looking from Fossil Ridge past the south end of Bluff Mesa over the Lowlands of the Irwin River Basin. Boulders of Fossil Cliff Limestone in foreground, with Upper Holmwood Shales beyond. Note flat-topped mesa of post-Permian "plateau sandstones" resting on the epi-Permian duricrust (black band about 20 feet below the top). (Photo: R. T. Prider.)

## 4. Lowlands.

In a distant view of the low-lying country all surface irregularities, and even streams and badlands seem to mingle into a wide area of uniform level, with only occasional residual mesas and buttes breaking the general flatness (*see* text fig. 2). Plate I (folding map) shows that the lowlands are composed mainly of shales with minor developments of limestone. Destruction of natural vegetation by settlers has exposed the shales to rainwash which has converted them into miniature badlands, and we have to thank the smallness of the rainfall for the preservation, even for this short time, of these small-scale models of physiographic features. The limestone bands, where persistent enough, form low ridges, asymmetric in cross section, which strike in a general north-westerly direction. The gentle dip-slopes of these ridges are characteristically dimpled with shallow depressions (known locally as melon or crab-holes) from six inches to a foot deep, and as much as 10 feet in diameter.



Text fig. 3—Eagle Hill, north of the Coal Seam Homestead. A typical small mesa capped by duricrust, blocks of which may be seen in various stages of undermining along the "breakaways." Photo taken in summer, showing only bare shrubs and small trees; in winter the ground is covered with abundant herbage. (Photo: R. T. Prider.)

## 5. Plateaux.

The low cliffs marking the edge of the plateau which has been incised by the Irwin River, owe their existence to a hard cap on the Permian rocks, rarely more than 12 feet thick, which is traversed by vertical joints (*see* text figs. 2, 3 and 4). This hard cap of duricrust (Woolnough, 1927) is very resistant to weathering, and undercutting and breaking away of large blocks often results (*see* text fig. 4). The name " breakaway " is thus quite appropriately applied in Western Australia to such cliffs, which occur in many regions and in varied geological formations.

The plateau behind the breakaways is covered with sand which supports a fairly dense growth of shrubs and small trees. In front of the breakaways are talus slopes formed by disintegration of the detached blocks, but in many places the soft shales and sandy shales underlying the duricrust are exposed and are cut into miniature badlands which extend down to the " lowlands."

Text fig. 4—Typical "breakaway" of the Irwin Basin. Soft strata beneath the duricrust are progressively undercut by weathering till large blocks fall away, as shown in the photo.
(Photo: R. T. Prider.)

In some localities the water, seeping out from below the duricrust along an underlying, gently dipping bed of shale has caused blocks of the duricrust to slip ; a large slip thus formed lies on the west side of the valley near Nangetty Homestead. Others occur around Mesas Nos. 2 and 4 and around Bluff Mesa.

In many parts of the Irwin River district the duricrust is siliceous and has a structure which simulates horizontal bedding. Woolnough and Somerville considered the nature of the hard cap (1924, p. 99) to be similar to that of the Darling Plateau laterites, and to be caused by deep weathering followed by concentration of hydrated silica near the surface of " an almost perfect peneplain " ; over the shale the cap is porcellanous, over sandstone it is almost a quartzite.

Overlying this epi-Permian duricrust, one may often observe a formation of ferruginous conglomerates, gravels, sandstones and silts. We cannot agree with Woolnough and Somerville that these " Plateau Beds " are purely residuals. They do not vary directly with the underlying Permian lithology ; on the contrary, the " boulders " in the basal conglomerate are mainly extremely well-rounded pebbles of quartzite and other Pre-Cambrian rocks. Campbell (1910) regarded these beds as continuous and contemporaneous with the Jurassic rocks known to the west ; Woolnough and Somerville rejected this correlation and regard them as Tertiary. While we agree with Campbell that the " Plateau Beds " represent an ordinary unconformable sequence resting on the Permian, we cannot at present suggest any precise age determination. In different places they appear to range through from Jurassic to Tertiary.

An interesting second duricrust is often found capping the ferruginous sandstones of the Plateau Beds ; it generally takes the form of a thin pisolitic laterite. The two indurated layers are well exposed, one over the other, in the cliffs ½-mile south of the junction of the North and South Irwin, where there are only six to 10 feet of the Plateau Beds. Up to 50 feet of them are to be seen overlying the epi-Permian crust elsewhere, for example, on Mesa No. 4.

### 6. Hills.

Island-like remnants of the plateau (*see* text fig. 3) rise from the lowlands and owe their form to the protective duricrust. Most of them are of the mesa type, though it is to be noted that their tops are not everywhere strictly horizontal. A careful comparison of the spot heights around the plateau margins suggests that there is a very gentle undulation in the epi-Permian peneplain (of Woolnough and Somerville, 1924, p. 99), and that the depressions in the latter correspond closely with the general course of the present drainage pattern. Numerous examples of buttes occur—Bugallie Hill, Gnoolowa Hill, Prider's Lookout, etc.

As mentioned previously, the limestone lenses have not weathered so easily as the shales and they have formed low cuestas running parallel to the general strike. These are particularly noticeable in the eastern part of the area just to the west of the elongated Bluff Mesa. In the western part the flatness of the lowlands is varied by the hummocky ground occupied by the glacial tillite, through which Mullewa Creek and its branches have cut.

The central, most resistant part of the Nangetty Glacial country, the Nangetty Hills, stands as a series of flat-topped hills, which are 100-200 feet above the surrounding country, being capped by resistant bands of "Fontainebleau" sandstone and residual boulders of the tillite.

## IV.—PERMIAN SUCCESSION.

The succession of rocks exposed in the northern part of the Irwin Basin is as follows :—

7. *Wagina Sandstone :* Mottled red and white sandstones, with intercalations of conglomerate, quartz grit and shale ; the shale contains plants but the rest is unfossiliferous. Thickness : 300 feet (plus)

6. *Caryngina Shale :* Rhythmically banded jarositic shales, passing up into fine banded sandy silts ; locally with fossiliferous marine lenses and conglomeratic lenses and packets of erratics near the base. Thickness : 800 feet

5. *Irwin River Coal Measures :* Sandstones and shales with lenticular coal seams and plant fossils. Thickness : 160 feet

4. *High Cliff Sandstone :* White and red sandstones and conglomerates. Thickness : 110 feet

3. *Fossil Cliff Formation :* Sandy siltstones, shales and mudstones, with lenticles of limestones. Rich in marine fossils. Thickness : 180 feet

2. *Holmwood Shale :* Rhythmically banded shales and mudstones, with ferruginous and calcareous concretions (some septarian nodules), and increasing amounts of jarosite and gypsum towards the top. Infrequent thin bands of limestone and calcareous mudstone containing marine fossils, otherwise generally unfossiliferous except near the top. Thickness : 1,650 feet

1. *Nangetty Glacial Formation :* Tillites, glacial shales, fluvio-glacial sandstones, locally with calcareous grits and sandstones showing "Fontainebleau" structure, underlain by further glacial shales and basal conglomeratic grits. Thickness : 800 feet estimated

Total thickness : 4,000 feet

The entire sequence may be followed without any clear indications of an unconformity, but is sharply separated from the Pre-Cambrian below and the " Plateau Beds " above by angular unconformities.

### 1. Nangetty Glacial Formation.

This name is proposed for beds which form a group of low hills, the Nangetty Hills, beginning N.N.W. of Nangetty Woolshed (lat. 28° 58½′ S., long. 115° 26′ E.) and extending thence S.S.E. beyond the limits of our map towards the Brockman Hills and beyond. The hills are entirely covered with residual boulders, likened by one observer to a gigantic moraine. Infrequent outcrops disclose tillites, glacial shales and fluvio-glacial sandstones.

The Nangetty Glacials disappear to the N.N.W. beneath the sand plain, but occurrences of tillitic boulders, in small outcrops or bores (*e.g.*, in Kockatea Gully, Balla, Dartmoor, etc.), here and there along this trend seem to confirm Maitland's correlation of these rocks with the Lyons conglomerate on the Gascoyne and elsewhere in the North-West Basin (1912).

A precise definition of the formation is difficult to give at present, since the basement is not well known. Woolnough and Somerville (1924, p. 77) believed that there are " Basal Grits and Boulder Beds " (resting on Pre-Cambrian in the Yandanooka-Arrino area), followed by " Sub-Glacial Beds," an unknown thickness of shales underlying the " Main Glacials."

The upper limit of the Nangetty Formation is marked by a transition from the glacial shales (with angular fragments and occasional boulders), into the dark grey shales of the Holmwood Formation.

Since the base of the glacial beds is not exposed in our area, or encountered in bores, it has been impossible as yet to measure the maximum thickness developed. Campbell (1910, p. 39) estimated that not less than 430 feet outcrop in the Irwin Basin. David and Sussmilch (1931, 1936) estimated that the main tillite beds were about 200 feet in thickness, the underlying shales 450 feet, and the basal glacial beds (fluvio-glacial) 150 feet. Teichert (1941) gave the thickness of glacials as 200 feet.

On the present survey it was confirmed that approximately 200 feet of tillites and fluvio-glacial beds occur at the top of the formation, and these are underlain by shales with small argillaceous limestone lenticles, while the basal conglomerates are beyond the limits of our area. Since the general character of these beds is essentially glacial, and no sharp divisions have presented themselves, it seems best to classify the whole sequence under the Nangetty Glacial Formation, taking the thickness as 800 feet.

The lowest glacial shales, which form the core of the structure depicted on our map, outcrop in a broad wedge south of Mungaterra Homestead. Since the shales contain lenticular bands of argillaceous limestone, they are in this aspect similar to the Holmwood Shales which overlie the Nangetty Formation, but differ from them in containing in places coarse, angular and fresh mineral fragments in a " rock flour " matrix. These are well exposed in several places in the bed of the Irwin from Mungaterra Homestead for some two miles downstream. When fresh they are quite hard and poorly stratified but weather readily, often in a spheroidal manner. A bore at the homestead penetrated 50 feet of these shales. At a point 600 yards south of Mungaterra they may be observed to be intersected by a number of sedimentary dykes filled with the argillaceous limestone commonly found in concretions ; the limestone dykes are affected by cone-in-cone structures from either side, and apparently follow minor faults which have been identified on the air photographs.

The shales are succeeded by tillites and fluvio-glacial beds, which outcrop mainly in the Nangetty Hills between Mungaterra and Nangetty. Woolnough and Somerville (1924, p. 81) describe the glacial beds *in situ* south-east of Nangetty Woolshed as : " bedded tillites of sandy nature, strongly cemented by carbonate of lime containing many erratics. Large and small lenticles of tillite are interbedded in the main mass of boulder clay." The boulder-bearing glacial beds are in places completely unstratified and may thus be terrestrial, but the evidence of banding in other sections indicates some degree of water-sorting. No varve shales were encountered.

Text fig. 5—Glacially striated surface of a large Pre-cambrian boulder, embedded in the top of the fluvioglacial sandstones of Tillite Creek, 50 yards east of the large silicified limestone erratic. The direction of the striations would indicate a northerly ice-movement if the boulder still occupies its original position. (Photo: R.W.F.)

In a small valley, one of the tributaries on the west of Mullewa Creek, named by us " Tillite Creek," the following section may be recognised in spite of some complication by faulting : hard tillite at the base followed by 20 feet of soft fluvio-glacial sandstones, capped by three feet of hard Fontainebleau sandstone, in which is cemented a large erratic boulder, and overlain in turn by a soft unstratified tillite. The large erratic is evenly striated over the whole of its upper surface (*see* text fig. 5) and may possibly have been already cemented *in situ* in the hard sandstone when a second glacial advance took place, over-riding and crumpling the fluvio-glacials and depositing the second tillites on top. The fluvio-glacial sandstones exhibit also subaqueous slump structures and cross bedding, which suggests current movements in a north-easterly direction. Some 20 feet of the second tillites reappear immediately to the east, in a down-faulted section (*see* text fig. 6). Down-stream and farther east, beyond another fault, there are stratified shales with small septarian nodules, of cannon-ball type, which may be mistaken at first sight for erratics. These shales are not glacial in character, and are thus taken to be near the base of the Holmwood Formation. Contact with the rest of the Holmwood Formation to the east is once again obscured by faulting.

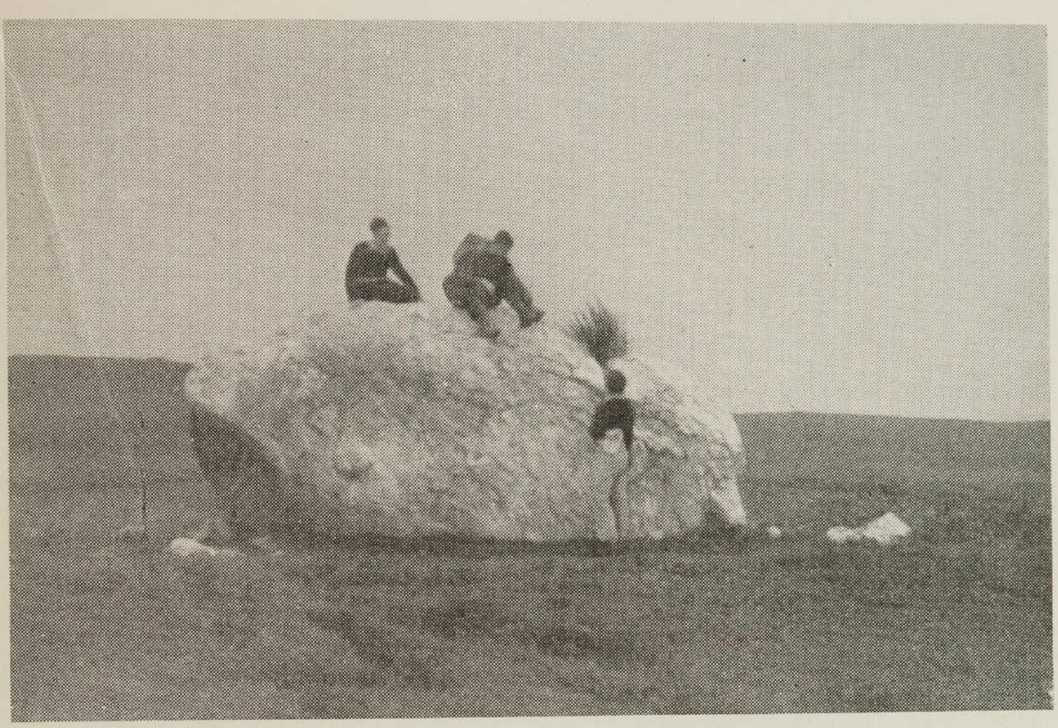
Text fig. 6—Characteristic exposure of unstratified tillite in situ in the bank of Tillite Creek. Boulders include true facetted boulders (of various Pre-cambrian rocks), as seen on the right, as well as water-rounded boulders of an earlier hardened tillite, seen on left. This older, more hardened tillite is exposed deeper in the section.

(Photo: R.W.F.)

Comprehensive surveys have not yet been carried out in these glacial beds and further work may disclose better sections.

The Nangetty Hills are plentifully strewn with boulders, and in some places where the streams are deeply incised the steep bank is seen to be composed of such boulders, fairly closely packed. The abundance of boulders on the hills and along the water-courses is partly due to concentration by removal of the smaller fragments by rain and wind, and is not an original feature of the tillite. The little cliffs of boulder material are due to excavation by streams of the alluvium which they themselves accumulated when the run off was restrained by vegetation, and consequently, deposition rather than transport was their major activity. We have not seen places where " there is a very strong suggestion that small erratics have been dumped in heaps by the capsizing . . . . . . of small rock laden floes " (Woolnough and Somerville, 1924, p. 81), and therefore agree with the alternative suggestion (*op. cit.* p. 82) that " the apparent grouping is everywhere a secondary feature."

The boulders include many rock types (almost all Pre-Cambrian). Only two or three have been microscopically examined, but the following list of field determinations gives some idea of their variety (the types are placed more or less in order of frequency) : reddish or blackish hard fine-grained mudstone, granite (four varieties), epidiorite (three varieties), chert, gneiss, pegmatite, quartz with epidote, mica schist (some much contorted), banded and brecciated quartzites, " contorted " silicified limestone, quartz schist, sheared conglomerate, quartz felspar porphyry, agglomeratic tuff.



Text fig. 7—The "White Horse" Erratic, situated one mile south-east of Mungaterra Homestead. It is a block 20 x 9 x 9 feet of faintly banded quartzite, which in places is brecciated, and may be partly a replacement product. It is believed to be of Pre-cambrian origin, for similar rocks of this character have recently been traced through the Yandanooka Group between Yandanooka, Coorow and Moora.
(Photo: R.W.F.)

Most of the boulders are rounded, but a few of the smaller ones show faceting and soleing, and some of the finer-grained varieties—particularly the mudstones—show characteristic striae. Nearly all the boulders are less than a foot across, but a few of gneiss and granite are as much as four feet in diameter, and a very few attain dimensions exceeding 10 feet in length. These last are always of the quartzite or silicified limestone mentioned above, the " White Horse " type (*see* text fig. 7), the original of which measures 20 x 9 x 9 feet. The rock composing these great boulders is sometimes referred to as a " cherty quartzite," and there appears to be a number of varieties of it grading into the banded and brecciated quartzites. These rocks, generally known as the " White Horse " type, after a prominent example of the partly brecciated massive quartzite, have long been the subject of discussion. Recently, the counterparts *in situ* were identified in the Pre-Cambrian Yandanooka Group, to the south, at several points between Yandanooka, Coorow and Moora. The varieties range from a scarcely banded quartzite, to a brecciated cherty quartzite, finally to the contorted silicified limestone. The brecciated rock may have been an intraformational breccia of thinly banded dolomites, or possibly cherts, in a calcareous shale, now replaced by silica, while the contorted rock is considered to be a silicified algal limestone, in which the contortions are taken to be stromatolitic algal structures, being very similar to those found in the late Pre-Cambrian in other parts of the world, and corresponding to the genus *Collenia* (*see* text figs. 8 and 9). Various stages in the replacement of the original limestone by silica have been found and examined under the microscope, but so far no cellular structure has been seen (samples 9102/3, 25133, 29956).* The best examples of this silicified algal limestone known *in situ* in the Yandanooka Group were found at milepost 157

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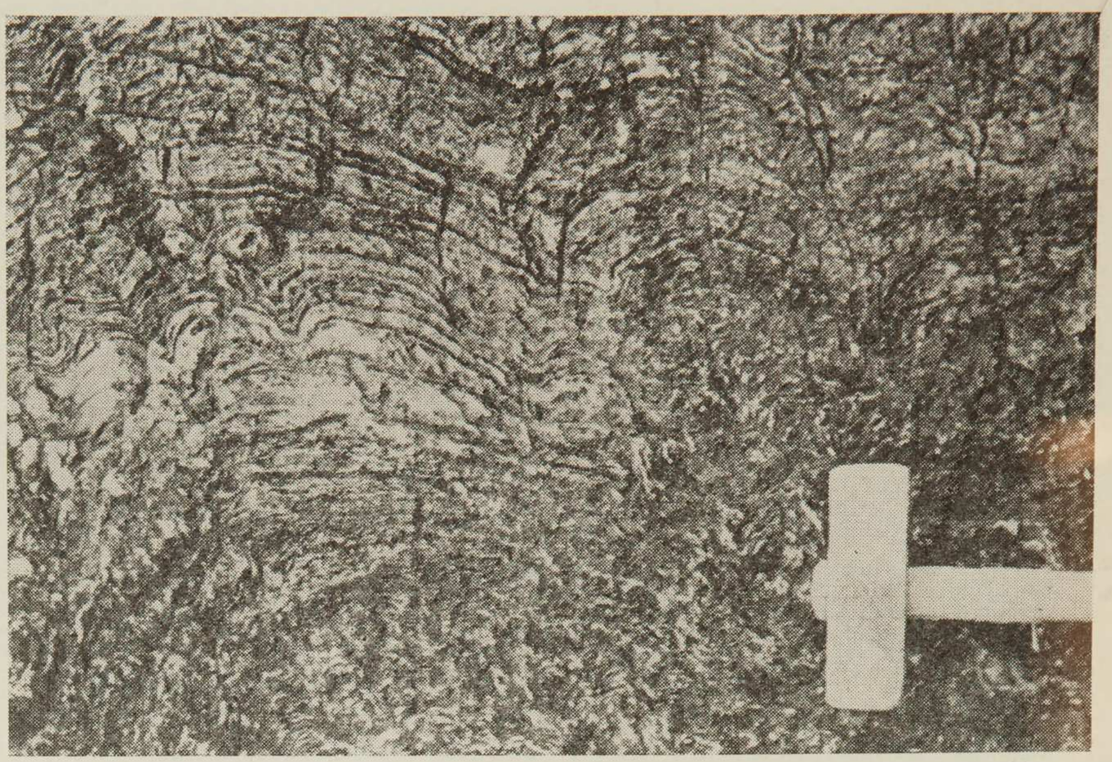
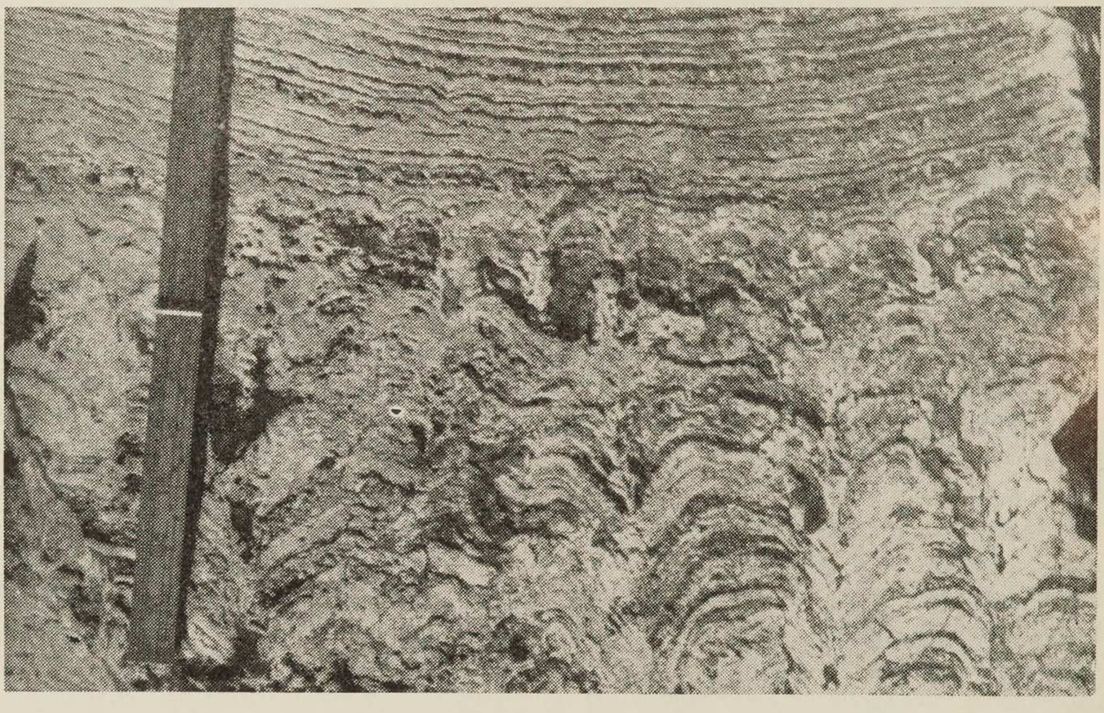
*Numbered specimens in the collection of the Geology Dept., University of Western Australia, are thus denoted in this paper.



Text fig. 8—Detail of a large silicified limestone erratic, situated in Tillite Creek, showing the alternate bands replaced by quartz. The concentric (stromatolitic) banding corresponds closely to the type of development of some algal reefs (Collenia) known elsewhere in the Pre-cambrian rocks.
(Photo: R.W.F.)



Text fig. 9—Same type of rock, photographed in situ near Gunyidi, 75 miles to the south, in rocks of the Y ndanooka Group.
(Photo: R.W.F.)

on the Geraldton road, about 70 miles to the south (R.W.F.).† A limestone boulder of the same stromatolitic algal banded type was recently found also in the Lyons Tillite (C.T.).

Occurrences of these very large boulders are, as far as we know, confined to three localities: the "White Horse," one mile S.E. of Mungaterra Homestead; Tillite Creek, where closely clustered large blocks occur, and a spot

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†A paper describing the Collenia rocks and their distribution in the Yandanooka Group has been presented elsewhere (Fairbridge, 1950).

a mile farther N.N.W. A glance at the map shows that these three localities lie in almost a straight line running N.N.W. Ordinary sized boulders of this particular rock are rather common along this line, and a few were noted in other parts of the field. It was thought at one time that these giant boulders might be the traces of a buried ridge, but from the present mapping, they appear simply to be characteristic of one of the important tillite members.

The development, noted by Woolnough and Somerville, of sandstone of " Fontainebleau " type (with the cementing calcite in crystal continuity) is particularly noticeable in the beds forming the more or less flat-topped hills north-west of Mungaterra. A laboratory examination of a three foot thick band of this " Fontainebleau " sandstone (sample 25727), resting on top of the fluvio-glacial sandstones in Tillite Creek, showed that it contained 22 per cent. calcite, while the underlying sandstones showed only 0.2 per cent. ; on the other hand, the insoluble minerals, mainly quartz, fresh felspars and a few heavy minerals, are almost identical in the two rocks. The grains are mainly angular, some slightly rounded, but are poorly sorted, consisting mainly of quartz grains with smaller amounts of felspars ; the latter are quite fresh and clear as a rule, only a few being somewhat kaolinized. There is some alignment in the grains. These observations confirm initial interpretation of the rock as a fluvio-glacial sediment.

## 2. Holmwood Shale

This name is proposed after the pastoral station (lat. 29° 02′ S., long. 115° 32′ E.) where these beds outcrop, for a succession of dark grey to buff-coloured shales (with minor developments of thin limestone bands) occurring both east and west of the Nangetty glacial beds. The boundary on the west is heavily faulted ; that on the east is also partially obscured by minor faulting and partly by alluvium, but there appears to be a conformable contact with the highest of the glacial shales of the Nangetty Formation. The uppermost limit of the Holmwood Shales is designated as the base of the fossiliferous limestones, siltstones, sandstones or their equivalents, of the Fossil Cliff Formation. The sharp change in lithology associated with the Fossil Cliff beds is taken as an indication of the formation boundary, not the appearance of stunted marine fossils near the top of the Holmwood Shales.

It was originally calculated that the total thickness of the Holmwood Shales, had there been no repetition by faulting, would have been 1,500 feet, according to Raggatt (1936), 2,200 feet according to David and Sussmilch (1936), and even 2,500 feet according to Teichert (1941). Recent work on the structure with the aid of air photographs, however, confirmed the existence of very considerable strike faulting (far more even than suspected by Prendergast and Luck, *see* Clarke, 1937), and the thickness is now calculated at about 1,650 feet.

Woolnough and Somerville differentiated six lithological members in this formation from top to bottom, namely, Olive Shales, *Gastrioceras* Bed, Buff Beds, Bull Paddock Limestone, Grey Limestone, and Spheroidal Marls. They note that these grade into one another, but state that the Bull Paddock Limestone constitutes a fairly persistent horizon and marks a transition in the conditions of sedimentation ; below it the beds are dominantly grey ; above it decidedly yellowish. They find that another change takes place immediately above the *Gastrioceras* bed, the Olive Shales being much less calcareous than the lower beds. Thus, according to these writers, the character of the sedimentation changed from dominantly calcareous in the lowest zones to calcareous and sideritic in the middle and to dominantly argillaceous in the upper zone.

The question of the subdivision of the Holmwood Shale needs further investigation. We have not been able to follow out the precise lithologic distinctions indicated by Woolnough and Somerville, but we recognise broadly an upper and lower division, with certain characteristic members :—

(a) *Lower Holmwood Shales*, outcropping immediately west of the Nangetty Glacials, around to the northern end of the Nangetty Hills and along their east flank, also in the valley of Mullewa Creek, Gnoolowa Creek, and in the lower part of Cat Creek. On the Irwin itself the exposures are generally rather poor. The thickness of the Lower Holmwood Shales is about 950 feet.

As noted above, the exact contact at the base is not seen, but in Tillite Creek, to the east of what appears to be a fault of very small throw, the soft grey tillite of the Nangetty Formation is succeeded by dark grey shales, weathering to a pale grey, of very similar external appearance to the tillite, except that the " boulders " in the shale are actually concretions, some of them septarian. The shale is greasy to the touch (even at the close of the dry season) and appears to be carbonaceous ; only locally does it contain marcasite or other ferruginous matter, in notable contrast to the Upper Shales. Laboratory examination (sample 25214 from Tillite Creek) confirmed that it was a poorly bedded clay to silty shale with occasional angular quartz and felspar grains or small pebbles. The felspars were rounded and moderately kaolinized. There was no calcium carbonate.

Another shale sample, taken near Cat Creek Dam (stratigraphically about 100 feet below the *Metalegoceras* horizon), was similar to the lower one, but very few grains were retained even by the 60 mesh Tyler sieve. Both calcium carbonate and ferruginous matter were absent. Associated with this shale were some large irregular concretions of limestone with cone-in-cone structure.

These lower shales were described by Woolnough & Somerville as highly calcareous, with a notably spheroidal weathering (their " Spheroidal Marls ") ; neither of these features, however, are sufficiently continuous or widespread to be used as distinguishing characteristics. (The Upper Holmwood Shales are also calcareous in places and certain bands weather spheroidally.)

The concretions appear to be of three types :—

(i) The " Cannon-ball " type, more or less spherical, ranging from three to 12 inches in diameter, containing an angular nucleus of shale or tillitic clay. These are apparently restricted to the horizons immediately above the tillite, and probably indicate that the tillite was being slightly eroded for a short time before burial in the advancing sea. The " cannon-ball " concretions are not banded spirally or concentrically, but appear to be perfectly homogeneous except for the " exotic " angular core. The latter appears to have acted as a nucleus for the precipitation of a calcareous-clay gel.

(ii) " Bun " or " Biscuit " type, more or less flat, circular in outline, superficially wrinkled to simulate the " culinary dainties " of Woolnough & Somerville. These mostly range from one to four inches across and are uniform in texture, but apparently lack any nucleus According to these authors they are probably secondary, being possibly " due to slightly different permeability of two adjacent shale bands, the concretion lying partly in one band, partly in the other." This type appears to be commonest in the vicinity of Urella.

(iii) Large ellipsoidal concretions, from one to six feet in diameter, and flattened to about one-third of this in height. These are found in the lower shales but are more common near the top of the upper shales (*q.v.*). They are often concentrically banded, without apparent nuclei, though sometimes they show septarian cracks partly filled with crystals of calcite. They occur on the Urella Block, half a mile above Yarragadee on the Irwin, near Copley's Mill, along Mullewa Creek, and in Cat Creek.

The origin of these various concretions has been briefly discussed by Campbell (1910, pp. 43–45) and by Woolnough & Somerville (1924, p. 85), but they clearly offer a subject for further research. The discussions in Twenhofel (1932, p. 708, etc.) present sufficient indication of some of the problems involved. An analysis by Simpson (in Campbell, *op. cit.*) shows that one example consisted of 73 per cent, $CaCO_3$, 13 per cent. silica, and 8 per cent. alumina, with a little iron, etc., so that they are strictly " cementstones " in character, having the composition approximately of Portland cement.

About 200 feet above the base of the Lower Holmwood Shales there begin to appear thin bands of grey crystalline limestone varying to olive-brown calcareous mudstone which generally weathers yellow. Generally they do not exceed one foot in thickness, but may reach five feet. Some of these are little more than large irregular concretions, but about half-a-dozen bands are very constant in their appearance at certain horizons, and some of them are almost continuous across the basin. These bands continue to the top of the lower shales. One of the lower bands, forming a prominent outcrop on the west side of Nangetty bull-paddock was called by Woolnough & Somerville the " Bull Paddock Limestone," and one near the top the " *Gastrioceras* Bed " after the goniatite (now named *Metalegoceras*).

A characteristic feature of most of these limestone bands in the Lower Shales, but apparently lacking in the Upper, is the widespread occurrence of cone-in-cone structure. Apical angles in the cones vary from 60 to 90 degrees. This structure is beautifully developed and exposed here. The general consensus of opinion nowadays indicates that cone-in-cone develops in a limestone where the calcite is fibrous, under conditions of vertical pressure assisted by slow downward solution (*see*, for example, Twenhofel, 1932, p. 732). It may be that the limestones in the Upper Shales are more sandy and do not favour this process ; or perhaps the structure is due to the increasing vertical pressure towards the base of the sequence. These cone-in-cone structures in the Irwin Basin, like the concretions, should repay further research.

About 20 feet below the highest band of cone-in-cone limestone which lies about 950 feet above the base of the formation, and which is taken, rather arbitrarily, as the top of the Lower Shales, there is a band of olive-brown calcareous mudstone containing the large goniatite *Metalegoceras jacksoni*, partly replaced by siderite, calcite and silica. The species is of considerable size : the largest specimen on record (No. 23405)—and even this is fragmentary—measures 205 mm. in diameter (Teichert, 1942). An even larger whorl has now been found, which belonged to an individual probably 260 mm. in diameter (No. 24794). This species was earlier referred to the genus *Gastrioceras*, and a single " *Gastrioceras Bed* " was marked by Woolnough & Somerville at this horizon. Careful mapping showed that in places in the eastern part of the basin there appeared to be several parallel bands, possibly distributed over a vertical thickness of 700 feet or so. One of us (K.L.P.) expressed the opinion that these actually represented a single horizon, repeated by strike faulting, and this has subsequently been demonstrated both on the air photos and in the field (R.W.F.).

On the western side of the basin, on the other hand, we have found *Metalegoceras* along one line only. Here the outcrops extend over less than a mile at the foot of the breakaways from one mile west of Nangetty to north of Macaroni Hill (*see* text-fig. 10). No fault duplication was found here, but in any case, on this side of the basin much of the country is obscured by alluvium or the plateau deposits.

Text fig. 10—One mile north-west of Nangetty Homestead. Showing breakaways capped by "plateau beds," overlying the Upper Holmwood Shales, with a band of calcerous mudstone containing *Metalegoceras jacksoni* in the foreground, just beneath Macaroni Hill.

(Photo: R.W.F.)

We were aware of the risk of mistaking for specimens *in situ* those which have been discarded by previous parties, and we have not shown any occurrences on the map which may not be verified both by being associated with the characteristic claystone and by being on the strike of a large number of other specimens. A further confirmation is found in the fact that specimens occur along the scarps of the cuestas, half way down the scarp in each case.

This unmistakable marker band may be clearly followed across the east side of the basin in a N.W.-S.E. direction from the vicinity of the Mullewa Road, four miles north of Nangetty, almost without interruption down to Holmwood Homestead No. 1, a distance of nearly 10 miles.

Probably visiting geologists, since Woolnough & Somerville examined the field, have taken away the goniatites more quickly than they were laid bare by weathering, but even so we cannot subscribe to published statements regarding their abundance. The *Metalegoceras* specimens are indeed found lying on or, much more rarely, embedded in, a richly calcareous buff-coloured mudstone, but even given the right outcrop, a search is generally necessary before specimens can be found.

*Metalegoceras jacksoni* has played an interesting role in discussions on the age of the glacial beds in Western Australia, and indeed in Australia as a whole. First described as a *Gastrioceras* (Etheridge, 1907), it was for some time considered to be a representative of the Upper Carboniferous genus *Paralegoceras* (Thomas, 1929, David & Sussmilch, 1931), until its true affinities were revealed by Miller in 1932. It is closely similar to early Permian representatives of the genus in other parts of the world (Teichert, 1941, 1942*a*).

One specimen of an orthoceroid and one fragment of a crinoid stem have been found in association with *Metalegoceras*.

Apart from the limestone and calcareous claystones, the highest 100 feet perhaps of the Lower Holmwood Shales show a distinctly yellowish or buff colour in the field, a feature which led Woolnough & Somerville to name them the " Buff Beds " (*op. cit.*, p. 87). There is no doubt that siderite plays an important role in the *Metalegoceras* beds, and these authors claim that it, with calcium carbonate too, occurs in greater amounts in the " Buff Shale " beds.

* * * * *

We turn now to the description of the upper half of the Holmwood sequence :—

(b) *Upper Holmwood Shales*, exposed from one to three miles below the junction of the North and South Irwin, about Gnoolowa Hill, in Eagle Creek, in Beckett's Gully and north-west of Bluff Mesa : light to dark grey shale and mudstone (Woolnough's " Olive Shales "), weathering to characteristic bands of olive-brown and grey soils. The shales are rythmically banded with layers of gypsum and reddish-brown ferruginous matter, which appears to be weathered marcasite. Large plates of selenite up to an inch thick and two feet across are secondarily deposited in joint planes. They are well seen one mile below the Irwin Junction.

The Upper Shales are, like the Lower, complicated structurally by faulting, but, according to the present measurements, reach 700 feet in thickness. Only two shallow bores have been put down in the eastern part of the Holmwood Shale area; these are Prest's No. 5 (176 feet) and No. 6 (24 feet), situated on the south side of the Irwin, half a mile and one mile respectively, south-west of the junction. As may be seen from the logs (*see* Appendix) they were not nearly deep enough to test the sequence of the Holmwood Shales.

On the extreme western side of the basin, very little reconnaissance has been carried out, but it may be surmised that the Upper Shales are represented beneath the breakaways and plateau beds west of Nangetty and west of Urella, since the *Metalegoceras* horizon (one mile west of Nangetty) represents the top of the Lower Shales. A series of bores was put down here near the edge of the plateau by the W.A. Boring Co. (Mr. Odgaard) in 1934, some details of which are :—

No. 1 (one and a half miles W. of Nangetty Homestead) passed through 13 feet of sand, (" Plateau Beds ") seven feet of duricrust, and then through sandy shales till reaching the " blue shale " (Holmwood Shale) just above bottom at 74 feet.

No. 2 (one and a half miles WNW of Nangetty) passed through 16 feet of plateau beds, reached the base of the kaolinized (epi-Permian) crust at 33 feet, and then passed a similar sequence of grey and yellow sandy shales to the blue shale at 64 feet, being abandoned at 83 feet.

No. 3 (one and three-quarter miles NW of Nangetty) passed through the base of the duricrust at 38 feet, and reached the blue shale shortly before 61 feet). All three bores brought in very small supplies of good water, just above the blue shale.

Finally, No. 4 (four and a quarter miles due N of Nangetty) was rather different, since after leaving the duricrust at 16 feet, it entered yellow and white sandstones and shales down to 38 feet (carrying water) before entering a grey shale which was penetrated to 45 feet ; this hole lies near the strike of the Nangetty Glacial Beds, but until more is known of this part of the area, it would be difficult to correlate these sandstones.

A series of bores has also been put down in the plateau lying to the north of the Irwin Basin on the Woongoondy and Mendel Estates (off the limit of our map), by the Public Works Department. While the bores, nine in number, are well-scattered, they appear to lie more or less along the strike of the Holmwood Shales, though some may penetrate the higher Permian formations. Almost without exception, they cut between 50 and 150 feet of red and white sandstones before entering alternating dark shales and mudstones. None of the bores exceeded 300 feet in depth.

To the south, between Yarragadee and Mingenew, numerous bores were put down by the Army about 1943–44. Of these, only one, A45, three and a quarter miles S by E from Yarragadee, seems to have penetrated the Holmwood Shales ; the log shows " blue shales " from 170-375 feet, but no water. The rest are either too shallow or lie farther west, and may be involved in a down-faulted block (*see* also under " Structure").

Near the top of the shales on the east side of the basin, alternating bands and small nodular concretions of pale yellow jarosite ($K_2$ $Fe_6$ $(OH)_{12}$ $(SO_4)_4$) occur, and this may be redeposited as a yellow powder over some of the gully slopes. A third sulphate, alunite ($K_2$ $Al_6$ $(OH)_{12}$ $(SO_4)_4$) is found associated with gypsum in concretions, *e.g.*, near the Coal Seam Homestead*. The shales appear to become more and more micaceous towards the top.

A laboratory examination of the shale (Sample 25728) collected three-quarters of a mile west of Toothagunna (" Nannygoat ") Swamp, stratigraphically about 25 feet below the lower of two prominent limestone bands there, showed fine clay minerals forming the bulk of the specimen, much in the form of small clay pellets, some 15 per cent. as gypsum crystals, negligible $CaCO_3$, and perhaps one per cent. carbonaceous matter. The sparce insoluble minerals included quartz, magnetite, ilmenite, limonite, leucoxene, brookite and kyanite (in 120 and 250 mesh Tyler sieve grades). A second sample (No. 25628), taken about 100 feet stratigraphically above the other, from about half a mile south-west of Toothagunna, was rather similar, containing 80 per cent. fine clay minerals, but no gypsum. The balance consisted of 19 per cent. very small angular grains of quartz and fresh felspar, with a few tourmaline and muscovite grains. $CaCO_3$ was about one per cent., and there was a trace of carbonaceous matter.

Rather large concretions of argillaceous limestone, associated with gypsum and alunite, are intercalated here and there at certain horizons in the shale. These are well-exposed in the gullies south of the river, one mile below Irwin Junction ; near the small butte, half a mile south-west of Toothagunna swamp ; and in Beckett's Gully, 200 yards above the road crossing. They

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* Both the alunite and jarosite here are secondary minerals, resulting from the breakdown of pyrite or marcasite nodules under neutral or acid conditions (Simpson, 1948).

are ovoid, ranging from one to six feet in diameter and are flattened to not more than 18 inches in height. The outermost layers are more clayey and weather spheroidally. The centres are extremely hard, but are not septarian as a rule, and no nuclei were found. The top is often puckered and ridged in the manner illustrated by Campbell (1910, fig 21). They appear to be chemical and syngenetic in character, *i.e.*, not due to contemporary rolling on the sea-floor, but to precipitation from an originally supersaturated solution of calcium carbonate and colloidal clay minerals, but, as noted earlier, there is clearly a need for further research on this interesting subject. Some small calcareous mudstone pebbles were found in Beckett's Gully (below the road crossing) with what appear to be sun-cracks on the surface (Sample 24636).

There are also five or six horizons of limestone, generally about one foot in thickness, varying from a grey crystalline limestone to a buff-coloured sandy limestone. These are more or less continuous though some long gaps may indicate that they are lenticular ; on the other hand, the broad alluvial fans, obscuring the outcrops, may explain some of these gaps.

Fossils are not common in these Upper Holmwood Shales, being mainly restricted to small pockets in some of the limestone bands, particularly the more sandy facies, and to thin bands in the shaley mudstones towards the top of the section. The fossiliferous limestone concretions were found in 1939 in Beckett's Gully, and on the 1949 excursion fossiliferous mudstones were discovered in a single band in the gullies south of the Irwin River, one mile below the Junction (Sample 25631). On the same trip fossils were found in the limestone bands 600 yards east of Eagle Creek and 1,100 yards west of Toothagunna (" Nannygoat ") Swamp ; and again, in the creek just west of the track 1,000 yards north of that swamp. These fossils are all rare and dwarfed, and include *Chonetes pratti*, *Chonetes* sp. nov., *Linoproductus foordi*, *Linoproductus* sp., *Conularia*, *Bellerophon*, *Soleniscus*, a small pelecypod, a nautiloid, and markings which appear to be coprolitic (Samples 25726, 29961).

The stratigraphic position of these fossiliferous limestone and shale horizons may extend as much as 500 feet below the base of the Fossil Cliff beds, but the possibility remains that unseen strike faulting has caused us to exaggerate the thickness. (This part of the section is not covered by air photographs, and in any case is not well exposed.)

Another very important fossil band was found on the 1949 excursion at about 550 feet below the Fossil Cliff Formation and 150 feet above the band of *Metalegoceras jacksoni*. So far it has only been found in the paddock, 200 yards west of the Nangetty/Holmwood boundary fence, almost exactly one mile north-west of Prider's Lookout (Sample 25632). It contains two new goniatites, which are as small (10-15 mm.) as *Metalegoceras jacksoni* is large, together with a nautiloid, *Chonetes pratti*, certain pelecypods, gastropods, and *Conularia*.

On the west side of the basin, the lenticular limestones have also been found, but only in one locality—one of the foothills lying against the western breakaways about one mile north-west of Nangetty Homestead—have fossils been found in any abundance. The hill is marked by a band of dense limestone through which ramify calcareous tubes filled with yellow material. Although the tubes twist about they do not appear to branch. They are evidently serpulids. The late E. Eckermann, formerly manager of Nangetty Station, who discovered this and many other geologically interesting features of the Irwin River district, named this limestone hillock Macaroni Hill, for obvious reasons, and it is given this name on our map.

This serpulid reef appears to lie somewhat higher stratigraphically than the *Metalegoceras* horizon and thus occupies a position near the base of the Upper Holmwood Shales. It contains a rather peculiar pelecypod and gastropod fauna, on which very little work appears to have been done to date (Samples 9101 and 16419). This fauna is quite different from that of the Fossil Cliff Formation. Brachiopoda are absent, and the most abundant fossils are nuculid pelecypods and a species of *Conocardium*. Foraminifera, as yet unidentified, are also present. The reef is restricted in this locality to the single little hill, outcropping over about 50 feet along the strike and up to three feet in thickness. Immediately underlying the reef facies is a blue gypseous shale with *Fenestella* sp.

A second lens of an identical serpulid reef limestone was found in 1949 by Mr. L. de la Hunty of the Geological Survey of Western Australia (personal communication) in the south-eastern part of the basin, four and a half miles south-east of Mt. Budd (12 miles east of Mingenew). Further surveys here have (R.W.F.) proved the extension of these lenticular outcrops over four miles along the strike ; they contain, besides serpulids, goniatites, orthoceratids, brachiopods, pelecypods, gastropods, crinoids and *Conularia*. This additional fauna suggests a correlation of the Macaroni Hill member with the goniatite limestone which lies one mile north-west of Prider's Lookout.

The lower limit of the Upper Holmwood Shales may be conveniently taken at the limestone horizon which lies 20 feet above the *Metalegoceras jacksoni* band. Woolnough and Somerville (1924, p. 88) indicated that this was a very abrupt break, but it hardly seems as sharp as they suggested. Admittedly the gypseous character of the shales becomes rather suddenly important but no sudden change in the calcareous constituents was noticed. Allowing for " rolls, folds and faults " in these upper beds, Woolnough and Somerville reckoned that they probably reached 1,100 feet in thickness, and after further mapping and the precise delineation of many of these structural disturbances, we are able to give the thickness as 700 feet, but again, there remains a possibility that there are still unrecognised structural complications.

The country composed of the shales is generally flat, but is broken to the east of the glacial beds by low cuestas around Bluff Mesa. The hard limestone bands influence the development of these cuestas and seem also to control the gentle undulations in the less deeply weathered country to the north-west of Bluff Mesa (" Charlie's Hill ").

The gypseous shales weather very easily to a fine powder and solution has developed " melon " holes in the flat country, *e.g.*, north of Cat Creek, and an underground drainage with sink holes and miniature canyons around the foot of the breakaways, and near the edges of the gullies, producing a well-developed bad-land topography.

### 3. Fossil Cliff Formation.

The gypseous shales of the Holmwood Formation are conformably overlain by dark, poorly fossiliferous, carbonaceous shales, mudstones, and brown and white sandy siltstones, which contain lenticular occurrences of richly fossiliferous limestone. The shales and siltstones often contain appreciable amounts of gypsum, jarosite, and marcasite, which suggests a continuance of special conditions of sedimentation (*see* discussion under " Geological History "). Thus, in sections where the limestone facies is absent, it has often proved difficult to distinguish the base of the Fossil Cliff shales from the very similar beds of the Upper Holmwood Formation. The gypsum and other soluble salts probably account for the presence of highly saline springs at approximately the base of the formation on the North Irwin (Warraga Spring), at the foot of the breakaway three-quarter mile north of Coal Seam Homestead, in Beckett's Gully, etc. This formation was named already by Woolnough & Somerville (1924, p. 91), the "Fossil Cliff Beds" after the occurrence at Fossil Cliff (lat. 28° 56½'S., long. 115° 32½'E.). It is succeeded conformably by the white and red sandstones and conglomerates of the High Cliff Formation.

The formation is most easily distinguished in places where the limestone facies occurs. Thus, in Beckett's Gully, gypseous shale of the Holmwood Formation is overlain by two feet of richly fossiliferous, yellow sandy marl, succeeded by a six inch band of hard crinoidal and brachiopod limestone, passing up into a sandy limestone, sandy shales and brown siltstone, which forms the gentle escarpment of Fossil Ridge and which outcrops nearby in the south branch of Beckett's Gully below Round Hill. Fossils are difficult to collect in the hard grey limestone, but are readily found where weathered out from the underlying yellow sandy marls, where dozens of corals, crinoid stems, etc., may be collected in a few minutes.

Text fig. 11—Fossil Cliff on the North Irwin, looking north-west. Shows alternating bands of fossiliferous limestones and gypseous shales. Note landslips in the latter. This is one of the best known and most oft-visited fossil localities in Western Australia.

(Photo: A. J. Glance.)

The type section is on the North Irwin at the locality called Fossil Cliff (*see* text fig. 11), where the fossils are in a friable and in part gypseous mudstone or sandy shale, from which good specimens are easily obtained. These fossiliferous bands are intercalated in a general sequence of friable sandy and gypseous shales and mottled blue and brown shales with jarosite and marcasite (or pyrite). Some current bedding is seen in the sandy beds. A narrow band of blue fossiliferous limestone occurs near the base of the shales which outcrop for 200 yards on the west bank. This section has been illustrated by Campbell (1910, p. 50) and measured (in part) by Raggatt (1936, p. 150), who gave the thickness as 75 feet. This was increased to 190 feet by Teichert (1941, p. 376), since when there has been no further study of these beds, except that we have placed the topmost beds in the High Cliff sequence, thus reducing the thickness to 180 feet.

On the opposite bank from Fossil Cliff, about 300 yards downstream, there is another impressive outcrop know as High Cliff (*see* text fig. 12), which does not expose the fossiliferous limestone, but only poorly preserved fossils, especially *Fenestella* and *Linoproductus* in brown, szndy siltstone, intercalated in the shales and mudstones (*see* fig. 26, in Campbell, 1910). The upper part of the cliff shows the contact with the white sandstones of the overlying High Cliff Formation (marked in part *?* Jurassic, by Campbell).

About three-quarters of a mile to the south, in the bank of the South Irwin, immediately west of the outcrop of the Coal Measures, there is a reappearance of these soft brown siltstones*, with bands of bright yellow jarosite, and several beds were found to be highly fossiliferous, being packed with crinoid stems, *Spirifer*, *Productus*, etc., the typical Fossil Cliff assemblage. Woolnough (*op. cit.* pp. 91–92) described the beds as "soft kaolinised sandstones" but only recorded part of an *Aviculopecten* ; we were able to confirm his comment that the hard limestone band at the base of the formation seems to be quite lenticular.

The connection between the South Irwin and the Fossil Ridge—Beckett's Gully outcrops is hidden beneath the overlapping beds of the plateau, east of the Coal Seam Homestead. However, the strike in both places would not indicate a direct connection between the two, but suggests displacement by strike faulting (*see* under "Structure"). To the S.S.E. of Beckett's Gully and Round Hill the beds disappear once more beneath the escarpment on which Holmwood No. 2 Homestead stands.

Just to the north of this spot, in 1949, a rich fauna was discovered in shales and siltstones on either side of Bangarra Hill (samples 29949 and 29951).

The rich fossil fauna of the Fossil Cliff Formation has not yet been described in full. It is almost certain that, with the exception of *Metalegoceras jacksoni*, all earlier records of fossils from the "Irwin River District" are from these beds, and fossils of that age are among the earliest ever recorded from Western Australia (J. W. Gregory, 1849) ; in 1861 T. Rupert Jones (in an appendix to F. T. Gregory's paper) reported the presence of *Spirifer*, *Productus*, *Pleurotomaria*, *Nautilus*, *Cyathophyllum*, and crinoid stems among Gregory's collections from the Irwin River.

Since that time, work on Fossil Cliff fossils has proceeded intermittently and some groups are now better known than others (Etheridge, 1889, 1907 ; Foord, 1890 ; Hinde, 1890 ; Newton, 1892 ; Howchin, 1893, 1895 ; Chapman, 1904 ; David, 1905 ; Glauert, 1910 ; Prendergast, 1934, 1943 ; Hill, 1937,

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* A laboratory analysis of the fossiliferous brown siltstone (sample 25623) showed it to be extremely well-sorted with about 35 per cent. fine clay minerals and 14 per cent. $CaCO_3$ ; of the heavy fraction there was 55 per cent. gypsum, 40 per cent. marcasite, and 5 per cent. accessories (staurolite, tourmaline, etc.), while in the light fraction 70 per cent. was quartz and 30 per cent. moderately weathered felspars. No oraminifera were detected.

1942 ; Teichert, 1941, 1944, 1949 ; Stubblefield, 1944 ; Crespin, 1947). In the following, therefore, generic and specific names are included in so far only as they are based on modern revisions of the fauna. In addition, general characteristics of the composition of the various groups are given :—

*Foraminifera* (Crespin, 1947) :

*Ammodiscus millettianus* Chapman
*Calcitornella stephensi* (Howchin)
*Trepeilopsis* cf. *grandis* Cushman & Waters
*Hemigordius schlumbergeri* (Howchin)
*Endothyra* cf. *media* Waters
*Nodosaria irwinensis* Howchin
*Nodosaria* sp.
*Frondicularia woodwardi* Howchin

*Anthozoa* (Hinde, 1890 ; Hill, 1937, 1942) :

" *Amplexus* " sp.
*Gerthia sulcata* (Hinde)
*Plerophyllum australe* Hinde
*Euryphyllum trizonatum* Hill

*Echinodermata* :

*Calceolispongia digitata* Teichert (1949) is the only species of crinoids so far described. In addition, crinoids of actinocrinitid and platycrinitid affinities are known to occur (Glauert, 1910). Crinoidal stems and columnals are fairly common in the limestone.

*Bryozoa* :

This group has not been studied, but our collections include representatives of *Fenestella, Polypora, Rhombopora, Hexagonella* and *Streblotrypa*. *Stenopora leichardti* was recorded by Chapman in 1904.

*Brachiopoda :*

This class is most abundantly represented in the limestone facies and certain species also occur in the shaley facies. Most common are productids and spiriferids, of which only some of the former have been treated more recently (Prendergast, 1934, 1943). These include *Dictyoclostus callytharrensis* Prendergast, *Linoproductus bellus* (Etheridge), *Linoproductus cora* var. *foordi* (Etheridge), *Strophalosia etheridgei* Prendergast, *Strophalosia* cf. *gerardi* King, *Strophalosia tenuispina* Waagen, *Chonetes pratti* Newton.

The Spiriferacea are richly represented by several species of *Spirifer* (s.l.) and by *Cleiothyridina macleayana* (Etheridge). In addition there are species of *Streptorhynchus, Dielasma* and other genera.

*Pelecypoda :*

Next to the Brachiopoda this is the fossil group which is best represented, but all the species are either undescribed or in need of revision. Among the genera now recognised in our collection are *Edmondia, Sanguinolites, Stutchburia, Aviculopecten, Deltopecten, Conocardium, Schizodus,* and *Allorisma.*

*Gastropoda :*

These include several species of *Bellerophon, Macrocheilina, Ptychomphalina,* and *Conularia.*

*Cephalopoda* (Teichert, 1941) :

Nautiloidea are rare and include undescribed species of *Pseudorthoceras, Euloxoceras, Domatoceras* and *Stearoceras.*

*Trilobitae* (Stubblefield, 1944) :

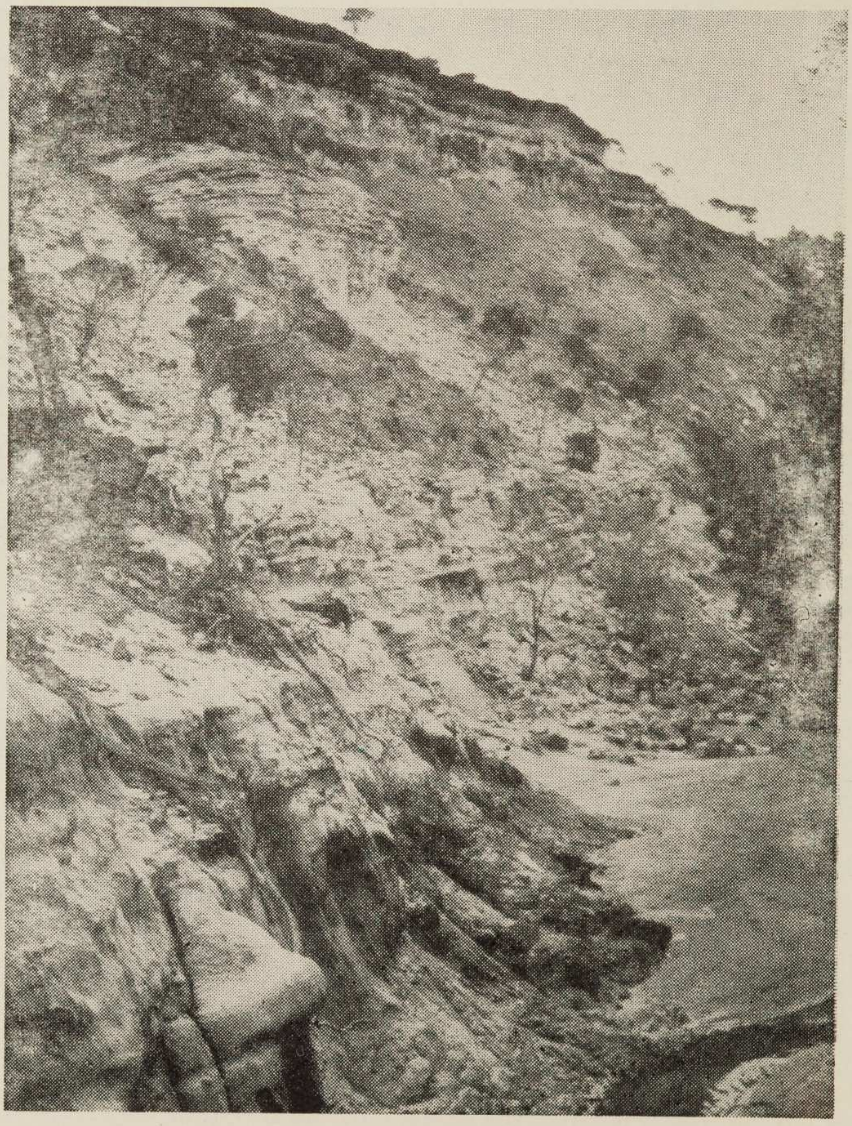
*Ditomopyge* sp. is the only trilobite known.

*Ostracoda :*

This group is represented by a number of undescribed species, some of which belong to the genera *Bairdia* and *Healdia.*

## 4. High Cliff Sandstone.

Overlying the Fossil Cliff shales and limestones, with a notable change in lithology, follows a sequence of white and red sandstones and conglomerate, which are best exposed at High Cliff (lat. 28° 56½'S., long. 115° 32½'E., on the east bank of the North Irwin, 1,100 yards above the junction) (*see* text fig. 12). These rocks were named the " High Cliff Beds " or " High Cliff Sandstone " by Dorothy Carroll (1945, pp. 86–7), but were not clearly defined. We are including therefore, an additional 15 feet of sandstone which she placed at the top of the Fossil Cliff Formation, apparently under the impression that there was a discordance above this sandstone. Insufficient evidence for such a break has led us to group all the sandstones together. The suspicion of such a discordance seems to have come first to Prendergast and Luck (*see* Clarke, 1937) on account of the sporadic occurrence of the Fossil Cliff limestone and certain apparent differences in strike between the upper and lower formations of the basin. The former is now regarded as due to facies changes and the latter to strike-fault displacements.



Text fig. 12—View of High Cliff, on the east bank of the North Irwin, looking south. Shows contact of High Cliff formation of red and white sandstone with the blue-grey shales and brown siltstones of the Fossil Cliff Formation in lower third of section.

(Photo: R. T. Prider.)

The High Cliff section was illustrated by Campbell (1910, fig. 26), but in the measured sections listed by Raggatt (1936), Teichert (1939, 1941, etc.) and other authors, it has either been partly omitted or included with the Coal Measures. The section measured by the Geology Department, 1939 excursion (according to Carroll, *op. cit.*) is interpreted as follows :—

| | | |
|---|---|---|
| Coal Measures— | Carbonaceous shale, etc. .... .... | .... |
| High Cliff Sandstone | Sandstone (shaley) .... .... .... | 28 ft. |
| | Grit or fine conglomerate .... .... | 6 ft. |
| | White sandstone .... .... .... .... | 56 ft. |
| | Current-bedded sandstone .... .... | 8 ft. |
| | Fine white sandstone .... .... .... | 15 ft. |
| | Total .... .... .... .... | 113 ft. |
| Fossil Cliff Formation— | Blue, micaceous shale, etc. .... .... | .... |

Text fig. 13—Notable band of cross-bedded sandstone close to the base of the High Cliff Sandstone, on the east bank of the North Irwin, about a quarter of a mile north of High Cliff. The direction of the cross-bedding indicates a current direction from the north. The figure is that of Sir T. W. Edgeworth David, whose early work on the correlation of the Irwin River Permian is acknowledged in the text. (Photo: E. de C. C.)

Incomplete exposures of these rocks were found in both North and South Branches of the Irwin, dipping 10° east beneath the Coal Measures. In two deep bores P.W.D. Nos. 1 and 2, put down in 1920–21 farther up the South Irwin (*see* map), the same formation has been identified at the base of the Coal Measures, but the upper boundary is not sharp, passing gradually, it appears, into the sandy and carbonaceous shales of the Coal Measures type (*see* text fig. 14). Thus in bore No. 1 there are 70 feet of sandstones followed by 51 feet of sandy shales (total 121 feet), and in No. 2 there are 76 feet of sandstones followed by 23 feet of sandy shales (total 99 feet). In bore No. 2., below the first true seam, there are 17 feet of shales with thin coaly bands which appear to be transition beds. The average thickness may be taken as about 110 feet.

These sandstones are quite unfossiliferous, the only characteristic being the cross bedding, which suggests a current-source to the north (*see* text fig. 13). The angle and thickness of the inclined beds suggest water-laid conditions.

According to Carroll's work (*op. cit.*) on the petrology of the sediments, the High Cliff sandstones at High Cliff are quite distinct from those higher up in the section, in being composed of well-rounded grains and having a small proportion of non-opaque grains to opaque grains in the heavy residues. Almost all the sandstones in the High Cliff and Coal Measures are very high in felspars, so that they are strictly "felspathic sandstones."

Following the strike to the south, the High Cliff sandstones form a prominent white bluff on the south side of the South Irwin, and then disappear beneath the breakaways to occur once more as the crest of Fossil Ridge to the east of the Fossil Cliff limestone outcrops south-east of Coal Seam Homestead, in Beckett's Gully, and on the top of Round Hill. They disappear finally beneath the breakaways below Holmwood No. 2 Homestead. The thickness in Beckett's Gully is difficult to measure precisely, but is of the order of 100 feet.

To the N.E., in Caryngínia Gully, there is a formation of sandstones and conglomeratic grits found up against the Darling Fault, dipping at 70° W.N.W., which appears to correspond to the High Cliff sequence (*see* text fig. 16). It underlies a thickness of plant-bearing shales and sandstones which are probably equivalent to the Coal Measures Formation, and these in turn underlie the Caryngínia Shales in the lower part of the valley.

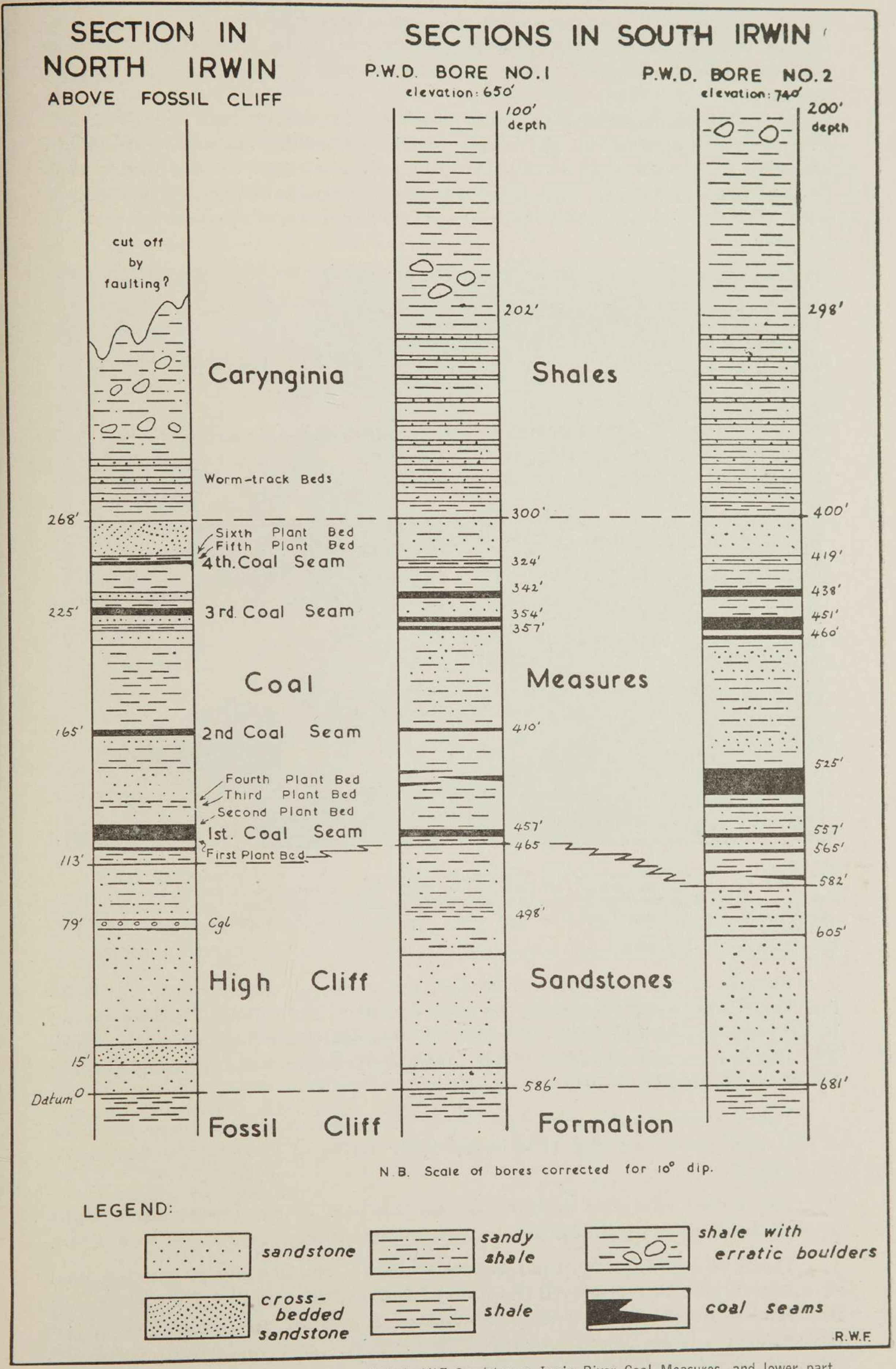
## 5. Irwin River Coal Measures.

The High Cliff Formation is overlain by a succession of shales and sandstones with some interbedded coal seams. This sequence of rocks has long been more or less loosely referred to as the Irwin River Coal Measures, a name which is here accepted and which it is proposed to define somewhat more precisely. The type section is taken to be on the North Irwin from one-quarter to half a mile above Fossil Cliff. The formation is conformably overlain by the jarositic shales of the Caryngínia Formation.

Outcrops of the coal measures were studied in the North and South Branches of the Irwin River, but the better known section is that in the North Branch (*see* text fig. 14).

The two deep bores (P.W.D. Nos. 1 and 2) put down farther up the South Irwin, and already referred to above (*see* also Appendix and text fig. 14), each disclose complete sequences of the Coal Measures, which not only correlate closely with those in the bed of the North and South Irwin, but also permit an accurate control of thicknesses to be made. Owing to seasonal movements in the alluvium of the two rivers, different sections of the bed are exposed from time to time, so that descriptions of the section by Campbell, Woolnough, Raggatt and others, are all somewhat incomplete.

The base of the Irwin River Coal Measures here is taken to be the carbonaceous shale, three feet below Coal Seam No. 1 in the North Branch (in Carroll's section, 1945, p. 86). This coal seam was found to be continuous in all available sections and bore logs (*see* text-figs. 14 and 15). Below it there is a gradual transition into the High Cliff Sandstone, which changes from a highly quartzose white sandstone upwards to a grey shaley sandstone, even showing



Text fig. 14—Stratigraphic sections of High Cliff Sandstones, Irwin River Coal Measures, and lower part of Carynginia Shales, as exposed in the North and South Branches of the Irwin River.

some carbonaceous partings near the top. The selection of the junction of the two formations had perforce, therefore, to be somewhat arbitrary. As noted above, Raggatt (1936) and others took a massive current-bedded sandstone, in our High Cliff sequence, as the base of the Coal Measures. It seems better stratigraphic practice, however, to reserve the Coal Measures Formation boundaries to the range of the essentially carbonaceous facies, although it is clear that the fundamental facies change to non-marine conditions, after the Fossil Cliff limestones and gypseous shales came abruptly with the unfossiliferous sandstones of the High Cliff Formation.

Text fig. 15—The best-known coal seam on the North Irwin. Looking north-east across Coal Seam No. 1. Geologists on the 1947 A.N.Z.A.A.S. excursion are seen collecting fossils from Plant Bed No. 2, which occurs near the top of the coal seam. Note also the well-developed terrace 10 feet above the river bank.

(Photo: R.W.F.)

Details of the North Irwin section are given in text fig. 14. In 1939 four coal seams could be seen in the river upstream from Fossil Cliff, separated by soft sandstones and shales in which six separate plant horizons were found. The distribution and character of the *Gangamopteris* flora were discussed already by Teichert (1942*b* ; 1943).

The *first plant bed* occurs just below the lowest coal seam near the base of the coal measures, and is crowded with leaves of *Glossopteris browniana* Brongniart.

The *second plant bed* is found in the top part of the lowest seam, eight to nine feet higher up in the section. It also contains *Glossopteris browniana.*

The *third plant bed* is found in sandy shale a few feet above the first coal seam and about 30 feet above the base of the coal measures. This is a richly fossiliferous horizon from which the following species were identified in our collections : *Phyllotheca australis* Brongniart, *Sphenophyllum speciosum* (Royle), *Glossopteris browniana* Brongniart, *G. indica* Schimper, *G. angusti-*

*folia* Brongniart, *G. decipiens* Feistmantel, *G. spathulo-cordata* Feistmantel, *Gangamopteris cyclopteroides* Feistmantel, *Sphenopteris lobifolia* Morris, *Cladophlebis roylei* Arber.

Just below the outcrop of the bed in the river bank there is a heap of harder white shales, most likely derived from the same horizon, containing well preserved plant impressions. It was probably from this occurrence that Glauert (1923) quoted *Glossopteris ampla* Dana and *Noeggerathiopsis*? sp., in addition to some of the species listed above. Furthermore, in correspondence some years ago, Dr. A. B. Walkom, recognised *Sphenophyllum* cf. *emarginatum* Brongniart and *Bothrodendron* sp. from collections made at the same locality.

A *fourth plant bed* is present three feet above the third. It is crowded with leaves of *Glossopteris browniana* and also contains *Vertebraria* sp.

In the succeeding beds no plants were found for a vertical distance of over 100 feet, but at about 149 feet above the base of the coal measures, a *fifth plant bed* was found in sandy shales just above the highest coal seam. This contains *Phyllotheca australis* Brongniart, *Sphenophyllum* sp., *Glossopteris browniana* Brongniart, *G. indica* Schimper, *Sphenopteris*? sp.

The *highest* (*sixth*) *plant bed* was found only two feet higher in the section. It is a purplish shale which contains poor remains of *Phyllotheca australis* Brongniart, *Glossopteris* sp., *Gangamopteris*? sp., *Bothrodendron* sp.

About one or two feet higher up follows a 16 foot layer of current-bedded and gritty sandstone, which forms the top of the sequence.

All the shales and sandstones, as well as the coal seams, appear to be rather impersistent, as is shown by comparison with conditions in the south branch of the river, though a similar grouping of seams is recognizable. Thus, in P.W.D. Bore No. 1 (*see* appendix and map) six coal seams, each one foot thick, were reported, while in P.W.D. Bore No. 2 there are said to be seven seams, one of which is 12 ft. 6 in. thick. Traces of some of these seams outcrop in the river bed of the South Irwin, though they are far from well exposed. It is clear, therefore, that the seams change somewhat in thickness and number over a distance of little more than two miles.

The same conditions of rapidly changing lithology apply to the shales and sandstones, and the fossil plant horizons are also lenticular. We did not recognise all the characteristic plant beds of the North Irwin section in the South Irwin, though admittedly we made less detailed investigations here.

Nevertheless, as may be seen from the vertical sections (text fig. 14), a careful comparison of the outcrops and bore logs shows that the overall thickness of the Coal Measures Formation is fairly constant, and if the High Cliff Sandstones are taken in with the Coal Measures, the figures (uncorrected for dip in the bores) are very similar :—

| | North Irwin. | P.W.D. No. 1. | P.W.D. No. 2. |
|---|---|---|---|
| Coal Measures .... | 155 ft. | 165 ft. | 182 ft. |
| High Cliff Sandstone | 113 ft. | 121 ft. | 99 ft. |
| Total .... | 268 ft. | 286 ft. | 281 ft. |

When the figures for the bores are corrected for dip, which appears to be about 10 degrees, a 5 per cent. reduction must be made, which reduces the No. 1 bore total to 271 feet and that of No. 2 to 267 feet. These corrections have been allowed for in the text figure (14). The average thickness of the Coal Measures is thus given as 160 feet.

As observed before, the smaller thickness of High Cliff Sandstone in P.W.D. Bore No. 2 appears to be due to a transition into Coal Measure facies, which formation is correspondingly thicker. However, the precise height of the lowest true coal seam above the base of the High Cliff Sandstone (*see* text fig. 14) shows that this is simply a lateral facies change.

It will also be seen that, owing to insufficient bore data, the top of the highest sandstone in the Coal Measures in Bore No. 1 had to be selected somewhat arbitrarily in the alternation of sandstones and shales which succeed the topmost coal seam.

To the south, the Coal Measures disappear beneath the beds of the plateau east of the Coal Seam Homestead. These reappear in the little amphitheatre about the head of Beckett's Gully, where the sequence is well exposed in the south (main) branch of the creek. Here we recognised no coal seams at all (they may be deeply weathered), only a thick series of completely bleached jarositic shales, with thin bands of sandy grit every few feet and with the prominent High Cliff Sandstones at the base (resting, in turn, on the mottled grey shales, siltstones and limestones of the Fossil Cliff Formation), and at the top overlain by the sandstone recognised farther north. The latter is transgressed unconformably by the horizontal beds of the plateau. The section is calculated to be about 150 feet thick.

The Coal Measures may be followed in the cliff below these breakaways for over a mile to the south, almost to Holmwood Homestead No. 2. At half a mile south of Beckett's Gully there is an exceptionally fine section, exposing 15 feet of brown carbonaceous shales with traces of plants at the base, followed by a band of cross-bedded sandstone with small slump structures and worm tracks, succeeded by alternating fine-grained ferruginous and micaceous sandstone and shale for eight feet, above which come bands of coarse quartz grits and white shale, before reaching the duricrust. A glacial erratic of hard quartzite over two feet in length was found at the base of the cliff.

Another quarter of a mile to the south, a point quarter of a mile north-east of Bangarra Hill, a slightly lower section is found. Underneath the brown carbonaceous shales come two feet of leaf beds, resting on a six inch seam of poor coal. Below this follows six feet of white sandstone and siltstones, resting on a ferruginous grit. In the leaf beds were recognised *Glossopteris*, *Gangamopteris* and *Noeggerathiopsis* (sample 29966). Numerous spore cases occur.

Almost in the direct line of the strike, in a well about two miles south-east of Holmwood No. 1 Homestead, the following strata (from above downwards) are reported :—

(1) Yellow clay.
(2) Red sandstone poorly cemented, with clay and mica.
(3) Laminated carbonaceous shale, containing leaf impressions.
(4) Sandstone and shale, with some leaf impressions.

Thicknesses were not given, but the first two sediment types are almost certainly belonging to the plateau beds, and numbers 3 and 4 appear to be of Coal Measure type.

In the other direction along the strike, there has been very little reconnaissance, but some of the deep embayments in the plateaus north of the North Irwin may be excavated in this formation.

The bores put down along the North Irwin and Dog Hole Creek (Prest's Nos. 1–4) were all singularly unfortunate in that each appears to have stopped just short of the topmost coal seam or to have gone down on the " wrong " side of an important strike-fault here. Nos. 5 and 6, though intended to search for coal, were begun in beds stratigraphically lower than the Coal Measures (below the Irwin Junction) and were thus more or less doomed from the start.

The principal result of the 1948 survey was the discovery of plant-bearing shales and sandstones reappearing farther east in Caryngìnia Gully, nearly in the line of the Darling Fault where they dip steeply to the west. Results of the work are as yet incomplete, but Permian fossil plants (including *Glossopteris*, *Gangamopteris* and *Noeggerathiopsis*) occur on both sides of the valley, and are associated with nearly 300 feet of sediments of lithology very similar to that of the Irwin River Coal Measures and the High Cliff Sandstone (*see* text-fig. 16). Occurrences in both localities are complicated by strike faulting, which fact would also explain the disappearance of most of the (less competent) coal seams.

Text 16—Near Caryngìnia Well No. 1. Quartzitic sandstones and conglomerates, probably equivalent to the High Cliff Sandstones, sheared, and dipping a 70° to the north-west against the main Darling Fault (which follows the small gully on the right). In the breakaways above the gully on the left there are plant beds, which probably correspond to the Coal Measures Formation.
(Photo: D. Sanders.)

In 1949 these outcrops near the Darling Fault were traced northwards to the large creek (unnamed) which joins the North Irwin one mile below Badgera Pool. Here there is a well-exposed sequence of alternating carbonaceous shales, silts and sandstones, dipping steeply west near the main fault, but severely dismembered by secondary faults downstream. Again, the coal seams, if originally present, have been lost owing to severe crushing.

Information concerning the coal seams of this stage of the Upper Palaeozoic rocks is too fragmentary to allow of much estimate of their value. It is known that several exist, ranging in thickness from a few inches to 12 feet and that their calorific value is low. Simpson (1929) states : " On the Irwin River field, five seams have been proved, all of poor quality." He gives the following analyses :—

| | *Tunnel. | †Bore, South Irwin. |
|---|---|---|
| Thickness of Seam | 5 feet | 12 feet |
| Fixed carbon | 36.83% | 28.75% |
| Volatile hydrocarbons | 26.89% | 26.81% |
| Ash | 13.92% | 22.63% |
| Moisture | 22.36% | 21.81% |
| Sulphur | 00.99% | .... |
| B.T.U. (as received) | 7690 | 6154 |
| B.T.U. (ash and moisture-free basis) | 12,068 | 11,076 |

* Probably No. 3 Adit, North Irwin.
† P.W.D. Bore No. 2, at 525 feet.

More recent samples have been analysed by Dr. C. R. Kent for the Midland Railway Company, whose kind permission to publish the results is gladly acknowledged. The first sample was collected in 1941 from a 30 foot vertical shaft in the South Irwin, three-quarters of a mile east of the crossing and one chain south of the river ; it was cut from a four foot seam, which is separated by a "flint" layer from another seam of sooty coal. This sample was carefully taken and packed to avoid exposure, so that the moisture content as given will be reasonably accurate. The second sample, from No. 3 Seam in the North Irwin, was collected by Dr. Carroll in 1939, but as no special precaution was taken against exposure it may have lost much of its original moisture.

Dr. Kent's analyses are as follows :—

| | Irwin River, South Branch, 1941. | Irwin River, North Branch, No. 3, 1939. |
|---|---|---|
| Proximate Analysis as Received— | % | % |
| Moisture | 32.17 | 18.5 |
| Ash | 7.24 | 19.0 |
| Volatiles | 25.44 | 27.05 |
| Fixed Carbon (by difference) | 35.15 | 35.45 |
| | 100.00 | 100.00 |
| Calorific Value, B.Th.U. per lb. as received | 7,725 | 7,195 |
| Ultimate Analysis Dry, Ash-free— | % | % |
| Carbon | 74.5 | 69.25 |
| Hydrogen | 4.95 | 4.6 |
| Nitrogen | 1.65 | * |
| Sulphur | 1.25 | * |
| Oxygen (by difference) | 17.65 | 26.15 |
| | 100.0 | 100.0 |
| Calorific Value, Dry, Ash-free | 12,775 | 11,510 |
| Sulphur distribution— | | |
| Calculated on dry, ash-free basis : | % | |
| Organic S. | 0.44 | |
| Pyritic S. | 0.67 | |
| Sulphate S. | 0.12 | |
| | 1.23 | |

Carbonate : Slight trace only.

* Nitrogen and Sulphur not determined.

Commenting on the results, Dr. Kent indicates that the Irwin River coals must be classified as *black lignites*, thus a stage slightly below the sub-bituminous coals, but the two analyses show that these coals are up to the level of the Griffin No. 1 and Cardiff Seams from Collie (based on ultimate analyses and classified on the Ralston system).

Finally, there is a report by Bowley (1946) of the old tunnel (believed to be that in the North Irwin No. 3 Seam) being opened up once more in 1944–45 when it was driven through to 180 feet along the seam. It was systematically sampled and proximate analyses given, but it was considered too high in ash for most commercial uses.

It would appear, however, that neither geological surveys nor drilling programmes have been sufficiently comprehensive to enable a just estimate of the value of the Irwin River coal seams to be made.

The heavy minerals of the Coal Measures sandstones have been made a special object of study by Carroll (1945), who came to some remarkably interesting conclusions. Most striking of her results was the recognition of a " flood " of garnets in the sandstones midway between coal seams Nos. 2 and 3 in the North Irwin ; the same horizon was picked up in the South Irwin. This feature distinguished this sandstone from all others in the area and should prove a valuable marker horizon in any future drilling. At the same time there is an increase in the proportion of non-opaque to opaque minerals in the upper beds. Carroll believes this sudden addition was due to the exposure to contemporary erosion (partly glacial) of the belt of garnetiferous gneisses, at present known in the Northampton-Greenough block, the nearest present exposure of which is 40 miles to the west. The rest of the Coal Measures sediments are such as one would expect to come from the Pre-Cambrian rocks immediately to the east of the present Irwin Basin.

Another interesting aspect, to which Carroll has drawn attention, is the way in which the grains in the sediments become progressively more angular, rising up in the Coal Measures. The fact that the felspars are fresh and unweathered, coupled with the reappearance of glacial erratics in the succeeding Caryngina Shales, could possibly be used to support the contention of Woolnough and Somerville (1924, p. 108) that " there is evidence of continued glacial action contemporaneous with coal deposition." Angularity and freshness of mineral grains may be accepted as evidence of rapid deposition, but not necessarily of refrigeration. However, the appearance of some large erratic in the Coal Measure may support this glacial idea.

## 6. Caryngina Shale.

The beds lying above the Coal Measures have not previously been very thoroughly examined. We propose the name Caryngina Shale Formation for them, after Caryngina Creek (lat. 28° 55½′ S., long. 115° 33½′ E.), which joins the North Irwin two miles north-east of Fossil Cliff and in which the beds are well exposed. They consist of a monotonous succession of jarositic and micaceous grey shales and silts, with thin bands of ferruginous sandstone and grit. The formation rests on the highest sandstone of the Coal Measures sequence and clearly represents a break in the freshwater succession, probably a return to the barred basin environment of the beds preceding the Fossil Cliff Formation, with their limited connection with the open sea. They are conformably overlain by the continental sandstones of the Wagina Formation (q.v.). Floating ice is suggested by the occurrence of occasional " dumped " erratics, especially in the lower part of the formation.

The presence of marine beds above the Coal Measures was already suspected by Woolnough and Somerville (1924, p. 96), who referred to these beds as the " Upper Marine." It was confirmed by David and Sussmilch (1931, p. 509, 1936), who reported the presence of 450 feet of mudstones " with Aviculopectens and *Anthracosia*-like shells and occasional fish." They also mention the occurrence of small erratics. Raggatt (1936, p. 150) described this upper series as " shale varying from sandy and micaceous to brown and carbonaceous, and with sandstone bands up to 18 inches in thickness near base." He confirmed the occurrence of erratics.

The base of the formation is well-exposed in three localities : in the North Irwin, immediately upstream from the Coal Measures ; in the South Irwin in a similar relationship (also in the two Public Works Department bores there) ; and in the upper part of Carynginia Gully where the westerly dip brings the Coal Measures up again near the Darling Fault.

There is a fairly abrupt change from the uppermost sandstone of the Coal Measures to a succession of jarositic shales with interbedded sandstone and lenticular ferruginous bands, as seen in both the North and South Irwin exposures. Only one pelecypod (unidentified) was found in these beds, and some of the shales contain indeterminable plant fragments.

Some of the ferruginous bands are ripple-marked and worm tracks are fairly abundant in them (sample 23147). The worm tracks are reminiscent of those found in the Permian of the Kimberley (Teichert, 1941, fig. 3). These tracks are so numerous in the lower sandstone band (12 feet above the base) that Carroll (1945, p. 86) referred to it as the " Worm Track Bed." They are exposed near the sharp bend of the North Irwin, half a mile N.E. of Fossil Cliff ; on the dip slopes of the western side of the valley, quarter of a mile to the north again ; on the east side one mile S.W. of Badgera Pool ; and in the South Irwin near the junction of Monday Creek, one mile S.E. of the Junction.

Farther south again, below the western breakaways of the South Irwin, the finely laminated micaceous silty shales (with jarosite, and thin bands of sandstone, grit and conglomerate) are exposed, dipping gently east. Micro-cross-bedding and small slumps of irregular orientation suggest the changing currents of a shallow-water sea.

In Carynginia Gully, on the northern breakaway, 800 yards N.N.W. of Carynginia Well No. 1, there is a band of micaceous silty sandstone close to the base of the jarosite shales which was found on the 1948 survey to contain abundant though rather poorly preserved marine fossils, most of which seem to belong to species already known from the Fossil Cliff Formation.

The following is a list of certain tentative identifications :—

(*a*) Brachiopoda :
    *Chonetes pratti*
    *Cleiothyridina* sp.
    *Linoproductus cancriniformis*
    *Linoproductus* sp.
    *Spirifer* cf. *curzoni*
    *Streptorhynchus* sp.
(*b*) Pelecypoda :
    *Pachydomus*, sp.
    *Parallelodon* sp.
Also, *Fenestella*, sp.

The lithologic sequence of these lower beds of the Carynginia Shales is well shown in the two P.W.D. bores in the South Irwin. These confirm the alternation of silty or sandy jarositic shales and thin sandstone bands for about 100 feet above the Coal Measures, above which are less sandy jarositic shales without sandstone bands. In No. 2 bore there are nearly 300 feet of these non-sandy shales. This same sequence, seen in Carynginia Gully, seems to continue, with very little change in character, right up to the top of the formation.

An interesting feature of the Caryngina Shales is the reappearance of occasional large erratic boulders, which appear to be ice-rafted, although none with glacial striae were noted. These are particularly common within 50 feet of the base in both the North and South Irwin but were struck in P.W.D. No. 1 bore 100 feet above, and in No. 2 bore nearly 200 feet above the base. In addition to the large erratics, occasional conglomeratic pockets of smaller pebbles occur. The largest erratic block measured two feet four inches in diameter.

The upper part of the formation is difficult to follow in the North and South Irwin valleys, where important strike faulting is suspected (leading to a sudden reversal of dip from about 10°E. to 10–14°W. and the appearance of the Wagina Sandstones overlying the shales). In Caryngina Gully, however, working downstream from Well No. 1, we encountered in 1948, an apparently undisturbed west-dipping sequence. The base crops out in the creek-bed about 400 yards below Well No. 1 and may then be followed right down the valley, to be capped about half-way up to the breakaways near its western end by the white sandstones and quartzitic conglomerates of the Wagina Formation. The same contact may be seen near the head of Dog Hole (Bigarra) Creek and along the eastern slopes of the South Irwin, at the head of Research Creek and about one mile N.W. of Wagina Tank.

Earlier estimates of the thickness of these "Upper Marine" beds have been given by David & Sussmilch (1931, 1936) as 450 feet ; by Teichert (1939) as 120 feet. However, these estimates were based on the impressions gained by very rapid reconnaissances, and not by an actual survey. Thus, unless there has been strike faulting that has been missed in Caryngina Gully, the steady westerly dips there would indicate a total thickness for the Caryngina Shales of 800 feet.

Examination by Carroll (1945) of the sandstones, her so-called "Worm Track Sandstones," near the base of the Caryngina Shales in the North Irwin, showed that the ratio of non-opaque to opaque minerals was considerably higher than in the Coal Measures. Of the significant minerals, garnet is less common than in the Coal Measures, likewise kyanite and staurolite ; limonite and zircon are most abundant. Quartz and felspars are in about equal quantities and the latter are generally fresh. Carroll believed that a sedimentary source from the west was indicated.

## 7. Wagina Sandstone.

Overlying the jarositic shales and silts of the Caryngina Formation, conformably but with a fairly rapid transition, there follows a succession of mottled red and white sandstones, with intercalations, higher up in the sequence of carbonaceous shales and of creamy white clay-shales, and at various levels bands of grit and conglomerate. The pebbles are rather small and probably not glacial. We propose to call this sequence the Wagina Sandstone, after Wagina Well in the South Irwin (lat. 28° 59½′S., long. 115° 35′E.). The top of the formation is not known, since it is cut off by the epi-Permian peneplain and the transgressive beds of the plateau.

Plant fossils are found in profusion, and beautifully preserved, in one of the shaley intercalations about a quarter of a mile east of Wagina Well on the north side of the valley of the South Irwin, but the rest of the succession appears to be unfossiliferous. Plant forms recognised include : *Glossopteris, Gangamopteris, Noeggerathiopsis, ? Annularia.* (Examination of the material is still in progress). About 20 feet stratigraphically below this plant bed there is an 18 inch band of carbonaceous, " coaly " shale, but it was too weathered for any plant fossils to survive.

The type section selected is that along the South Irwin, from a point one and a half miles south-east of the junction with the North Branch, upstream and in the breakaways on either side, as far as half a mile east of Wagina Well, a short distance east of the track crossing the valley and leading up to Hector's Well and Caryngina Well, where the main Darling Fault cuts off the sequence. The thickness of the Wagina Sandstone in the South Irwin is not less than 300 feet, but a complete section, as noted above, is not available.

The white sandstones may also be seen resting on the Caryngina Shales at the head of Research Creek (farther down the South Irwin) ; at the head of Bigarra (" Dog Hole ") Creek ; around the foot of the breakaways, east of the North Irwin and south of the Caryngina Creek ; and farther north again extending up towards Badgera Pool. This area has not yet been thoroughly examined.

Discussion of the character and origin of the sandstone must be deferred until it has been examined petrologically.

Some idea of the subsurface distribution of the Wagina Sandstone in the North Irwin may be obtained from the logs of Prest's Bores Nos. 3 and 4 (*see* Appendix). Prest's Bore No. 3, near Bigarra (" Dog Hole ") Spring, passes through the base of the sandstone at 108 feet. The next bore, No. 4, 660 yards east of No. 3, lies on the plateau, and after 31 feet of laterite and reddish sandstone (" Plateau Beds "), passes the base of the sandstone at 52 feet, thus suggesting a westerly dip. That the Wagina Formation is not all sandstone is indicated by the presence of shales (apparently lenticular) above the sandstone in bore No. 3. Bores Nos. 1 and 2 lie half a mile west and north-west respectively of No. 3, and only seem to penetrate Caryngina Shales.

## V.—STRUCTURE.

The first note on the structure of the area comes from Gibb Maitland (1904), who wrote : " The north-western (? north-eastern) boundary of the field is marked by a fault, which throws the bed against the crystalline rocks. In the vicinity of the fault the strata have been thrown into a series of gentle folds but the series has a prevailing dip to the eastward. To the west the beds dip at a slight angle, towards the sea, in such a way that the coal seams of the Upper Irwin should, if continuous, pass beneath the Mesozoic rocks of Mingenew and Depot Hill." This was the first recognition of what we now know as the main Darling Fault in this region.

Campbell (1910, Pl. V.) in his cross-section interpreted the general structure of the Permian in the Irwin Basin as a broad anticline, trending N.N.W. His interpretation was based on the fairly uniform easterly dips east of the Nangetty Glacials and the reappearance of the Holmwood Shales to the west of them. He did not describe any faulting in the Permian rocks except (p. 14) faulting and " crushing " against the granite in Caryngina Gully. In his section, however, on the east side of the basin he showed the east-dipping Permian formations abutting against the Pre-Cambrian along a steep contact but without a fault. Subsequent observers have tacitly accepted Campbell's anticlinal interpretation.

Further work by Woolnough & Somerville (1924), both here and in the surrounding country, made them suspect the existence of important normal faulting in meridional to N.W.–S.E. trends along the western borders of the Western Australian Pre-Cambrian plateau. They concluded that the " probability of the existence of a series of major step-faults throwing towards the Indian Ocean, is therefore reasonably well established." Recent work by one of us (R.W.F.) on the water-bore records of this coastal belt, including those completed by the Army during the war, as well as work on the regional geomorphology, has gone far to confirm Woolnough's preliminary suggestion.

The question of folding was not mentioned by Woolnough & Somerville, but both their map and section clearly depicted a broad anticlinal warp of symmetrical pattern, disposed along the N.N.W.–S.S.E. axis of the Pre-Cambrian ridge which runs through Yandanooka and Arrino, forming the Mullingarra and Brockman Hills. The feature was referred to by them as the " Mullingarra Axis."

It is possible, therefore, that this axis might extend northwards as a " buried hill." The gentle dips on the flanks, hardly to be seen at all on the west, would thus be interpreted at initial dips, modified to some extent by compaction. The fact that the easterly dips continue at 5–10° for some eight miles east of the axis may, however, be regarded perhaps as rather excessive for a " buried hill."

We thus possessed two working hypotheses prior to the recent surveys (1948–49)—the concept of a normal folded anticline, or of a buried hill, modified perhaps to some extent by strike faulting. The arrival of air photographs, coupled with further investigations, has, however, disclosed a far more complex structural pattern. In essence we must abandon the folding idea and return to Woolnough's general conclusion, that there are successive meridional fault-blocks of considerable dimensions, stepped down from the great Pre-Cambrian plateau in the east.

First of all, the Pre-Cambrian plateau is cut off by what is believed to be the northern extension of the *main Darling Fault.* It strikes very uniformly N. 20°W. Its throw, as noted by Woolnough & Somerville, must be not less than the thickness of the entire Permian, to which we may add that of the younger Pre-Cambrian sediments of Woolnough's Yandanooka Beds : these would be perhaps 4,000 and 3,000 feet, respectively, thus conservatively not less than 7,000 feet. The last movement on it in this sector would be post-Permian and probably pre-Jurassic (*see* also Raggatt, 1936). Earlier movements probably go back to Pre-Cambrian times. Today the fault-line possesses no physiographic expression, except where re-excavated by youthful stream revival, since both Permian and Pre-Cambrian rocks were peneplaned and later transgressively overlapped by a continental formation of partly Jurassic age which now occupies the flat-topped plateau. (These " Plateau Beds," as noted earlier, appear to range through from Jurassic to Tertiary.)

Secondly, there is what we have called the *Nangetty Fault,* which runs nearly parallel to the Darling Fault, about 10 miles to the west. It was first recognised on the air photographs running from west of Bugallie Hill through Nangetty Homestead to the S.S.E., following a rectilinear trend " like a railway line," till it disappears beneath the alluvium of the Lockier Basin, but appears to be continued in the line which abruptly truncates the Yandanooka-Mullingarra Pre-Cambrian ridge on the west side. The line disappears under Jurassic or younger sediments at either end, but even then is over 40 miles in length. In the Nangetty area it cuts off the Nangetty Glacials on the west, bringing in sediments apparently fairly high in the Holmwood Formation. Here the throw may be somewhere about 200 to 500 feet, and it may be dying out towards the north. Around Yandanooka, however, it may be much greater. Like the Darling Fault in this area the Nangetty Fault is probably pre-Jurassic in age.

Woolnough & Somerville did not recognise this Nangetty Fault, but indicated the *Urella Fault*, which lies closely parallel to the former about two to three miles farther west, running west of Urella, through Yarragadee, just east of Mingenew, and through Eyragulla Springs in the direction of Yandanooka. Our surveys have not covered this area very thoroughly, but it may be that in the south the two lines are one and the same.

The significant feature of this fault is that it involves fossiliferous Jurassic and possibly Cretaceous rocks ; in places they stand vertically. No Jurassic-Cretaceous movements are known in this region, and the displacement may well be Tertiary in age. However, the fault is truncated and overlain by the highest "Plateau Beds." Its character will be discussed further below.

It is also worth mentioning here, perhaps, in order to illustrate the regional pattern of this great step-faulting, that there is a fourth major line, Woolnough's Moonyoonooka Fault, which parallels the others 25 miles to the west again. It may be followed from just north of Geraldton, through Irwin House Station (on the railway six miles east of Dongara), apparently to die out in the Mesozoic sand-plains north-west of Moora (*see* text fig. 1). Like our Nangetty-Yandanooka ridge, this block also possesses a core of Pre-Cambrian rocks, which outcrop on the Greenough River and in the Northampton area. Its throw is not less than several thousand feet. Like the Urella Fault it is probably Tertiary in age.

It may be noted that in both cases the Pre-Cambrian basement comes to the surface near the *western margin* of each fault block, while the overlying sedimentary rocks may be seen (in the Irwin Block) to dip very gently to the east. Steep westerly dips are only found just along the fault zones. The tectonic picture presented is thus one of successive parallel step-faults, with the down-throws towards the Indian Ocean, and with each successive fault-block tilted so that the easterly side has slipped down and the westerly margin has tended to rise up antithetically.

There is thus no broad folding tendency in the region, and the only structures observed in the Irwin Basin are such as may be explained by major gravity faulting in the hard Pre-Cambrian basement, with minor adjustments in the soft sedimentary cover.

Thus, in detail, there is much of interest. Apart from the major fractures, numerous strike faults, of relatively minor throw (50-100 feet), have now been recognised. These, for the most part, appear to be not more than a few miles in length and generally die out on curving planes. They probably do not penetrate the Pre-Cambrian basement, but are taken up in the slippery shales. They are thus secondary and quite distinct in character from the major basement fractures.

Some overturning and dragging of the shales occur near these faults, and, in fact any dips much over 10° are found to be connected with them.

Most of these secondary faults throw down to the west, like the major fractures, but whereas the latter have near-vertical dips, the former generally dip gently to the west. Antithetic faults are rather uncommon, but are noted in the Holmwood Shale Formation. The only systematic east-throwing faults are those along the eastern border of the Nangetty Glacial Formation, so that the Nangetty Hills are a minor horst.

Reviewing the structural data, then, from the east to west, we find first of all the main Darling Fault, which brings the High Cliff Sandstone, Irwin Coal Measures, Caryngina Shales and Wagina Sandstone down against Pre-Cambrian. Owing to the softness of the sediments, the contact is generally rather poor. As noted by Campbell (1910, p. 14) the granite generally leads to slight falls or " rapids " on the river tracts, as at Badgera Pool on the North Irwin and in Caryngina Gully. It is less noticeable on the South Irwin. In all three a considerable drag in the sediments is recorded, resulting in fairly steep westerly dips (30° to 70°), which are most developed in Caryngina Gully. Westerly dips of 10°–15° persist down the length of this valley. In the South Irwin, however, west dips are seen only within a few hundred yards of the fault and are replaced downstream by gentle east dips.

About one and a half miles west of the main fault, in the valley of the North Irwin, there appears to be a secondary fault throwing east, which results in the Wagina Sandstones and upper Caryngina Shales being thrown down against the lower Caryngina Shales and Coal Measures. The throw would be about 200 feet near Bigarra Creek, 100 yards east of the North Irwin, and there is a flattening of the dip, from 10°E. in the Caryngina Shales and Coal Measures, to a westerly dip in the Wagina Sandstones.

There is some important faulting of easterly throw (apparently related to the above) along the South Irwin, where the dips are mainly 3° to 4° E., especially to be seen just below the breakaways, one mile west of Wagina Tank. Minor displacements were found one and a quarter miles south-west of Toothagunna (" Nannygoat ") Swamp, where one fault, in the sandy shales of the Caryngina Formation, shows a near-vertical movement, trending north, with indurated slickensides, but the displacement must be slight, since no change of lithology is to be seen. A few yards to the west there is a small antithetic fault, curving upwards to the south-west, and showing even vertical dips in the dragged up strata of the footwall.

Similar faulting of antithetic character is well exposed in a creek one mile south of Badgera Pool, where steeply west-dipping Coal Measures are brought down against Caryngina Shales dipping 21°E.

Additional minor movements were noted in the Coal Measures Formation in both the North and South Irwin, near the coal seams, and about High Cliff. They appear to have no far-reaching significance, and throws of only a few feet were seen.

Farther west, in the upper part of the Holmwood Shale, there are gentle dips, north-east at 3° to 4°, to be seen in gullies along the south side of the Irwin and in the " badlands " east of Eagle Creek. Excessive soil erosion in this area has assisted the geologist by exposing fresh sections in the soft shales, which are effaced again after one or two seasons.

About one and a half miles down the Irwin from its junction between the North and South Branches, there occurs another strike fault of the secondary type, trending N.W. to S.E. and throwing about 300 feet down to the west. This line controls the main course of Eagle Creek and so is referred to as the Eagle Creek Fault. North of the Irwin it cannot everywhere be seen beneath the broad alluvial aprons of the northern breakaways, but seems to continue for five and a half miles, to disappear finally beneath the plateau about one and a half miles north of Gnoolowa Hill. Some minor low angle faulting is connected with the main (vertical) displacement. The contact was not identified in the field, but is extraordinarily clear on the air photographs. The western side is involved in a broad synclinal drag over a width of 600 yards, where there are west dips, estimated at up to 15° or 20°. Woolnough (1924, p. 90) noted exceptionally steep dips on this line. A slight regional plunge to the south-east is noticeable from the outcrop of the beds on the air photos. In that direction, the fault disappears beneath the breakaways just one mile north of the Coal Seam Homestead and is not seen again.

Farther south, one and a half miles south of the Coal Seam Homestead, an excellent section is exposed in Beckett's Gully, but here the easterly dip is considerably steeper near the top of the Holmwood Formation, increasing from about 3° near the road-crossing to 9° at the base of the Fossil Cliff Formation.

It would seem that the Eagle Creek Fault is responsible for this anomalous appearance of the Fossil Cliff Formation, overlain also by 250 feet of the High Cliff Formation and Coal Measures, etc., dipping at 8°–9° north-east. Here the strike is N.N.W–S.S.E., which would carry the Fossil Cliff horizon *west* of the Eagle Creek Fault, were it not for the southerly regional plunge mentioned above. As it is, this horizon may be traced on the ground or in air photographs directly through the Coal Seam Homestead, but then disappears beneath the debris of the breakaways. Under the plateau here it is believed to swing around to the east in the synclinal drag of the fault, as noted already farther north-west. Since the throw is to the west, the Fossil Cliff horizon would then be displaced some distance to the south-east on the east side of the fault and would thus fall into alignment with the strike of these beds, where last seen just above the Irwin junction.

Below the Fossil Cliff horizon in Beckett's Gully there are fairly good exposures of the upper part of the Holmwood Formation, and no other fault has been observed. There are highly saline and gypseous springs (noticeable even in very dry seasons) a short distance below the base of the Fossil Cliff Formation here, again below the breakaways three-quarters of a mile north of Coal Seam Homestead, and yet again in the bed of the North Irwin, three-quarters of a mile above the junction (Warraga Spring ; *see* Campbell, 1910, p. 70) ; all appear to be related to a stratigraphic horizon just below the Fossil Cliff Formation, not to faulting.

It may be observed also that the convergence of strikes in the south-east, about Holmwood, might suggest a steepening dip or a reduction in the amount of faulting. Both factors seem to play a part.

To the west again of the Eagle Creek Fault, the steep dips quickly flatten and " normal " dips reappear (2°–4° ENE to NE) and continue until cut off by further strike faults. These are so numerous with many branches which die out, that it seems easiest to refer to them simply as the *Holmwood Fault Zone.* The zone may be followed clearly over a width of two miles from the north-west corner of the basin to pass through Holmwood No. 1 Homestead, in the south-east, a distance of over 10 miles.

The details of this faulting are beautifully displayed on the air photographs in the area between the Irwin and Holmwood No. 1 Homestead. Interpretation of the photos indicates that the throws are small, and mainly to the west, but varying in dip from near-vertical to quite gentle inclinations. It would appear that these faults in particular are of quite shallow depth and curve off downwards and laterally into the incompetent shales.

Abrupt changes in soil coloration may be seen on the ground, corresponding to the lithologic breaks between the more ferruginous and the more gypseous shales. Dips here average 5°–6° north-east, but reversals are seen on some of the faults. Best field exposures of the Holmwood Fault Zone are found about the four mesas on the north side of the Irwin, lying between Gnoolowa Creek and Mullewa Creek. South-east of Mesa No. 4 in a tributary of Gnoolowa Creek a limestone band dips 20° south-west, while between Mesas Nos. 3 and 4, a dip of 25°E. was measured. Numerous other irregular dips may be seen in the deep gullies in this area.

One of the most interesting features of this zone is the way in which the faulting duplicates the most important fossiliferous marker horizon of the Holmwood Shale, the *Metalegoceras jacksoni* limestone band. This repetition was regarded by some as stratigraphic, though one of us (K. L. P.) felt that strike faulting east a more likely explanation, and this hypothesis was confirmed by the recent interpretation of the air photographs (R. W. F.).

Other limestone bands in this section are generally much less fossiliferous, and so far have not proved useful in the calculation of fault displacements. Such calculations are thus extremely difficult in the otherwise uniform shale sequence.

There next comes another fault zone, parallel to the last, but one to two miles farther west again. It may be followed from near the head of Mullewa Creek in the north-west to the South Holmwood Homestead in the south-east. We have called it the *South Holmwood Fault Zone*. It is notably rectilinear, with near-vertical dips, and is distinct from all other important series of faults in this part of the Irwin Basin, in that the throws are mainly to the east. In this way, the tillites of the Nangetty Glacial Formation are generally brought into contact with the Holmwood Shales, but since both formations are lithologically very soft, the fault planes are more obvious on the air photographs than on the ground.

In the tributary west of Mullewa Creek, which we have called "Tillite Creek," there is evidence of three of these minor faults. The most easterly of them, which is not well seen, brings the "cannon-ball" (concretionary) shale of the lower part of the Holmwood Shale, dipping about 2° north-east, against the soft unsorted Nangetty tillites, which also appear to be tilted about 2° north-east. The next fault plane, 150 yards upstream, is perfectly exposed trending 155° and dipping 60° north-east ; on the west side the fluvio-glacial sands and sandstones with an underlying hard tillite are dragged steeply over. These fluvio-glacial beds are very irregular and have suffered glacial disturbance, but appear to be generally dipping about 3–4° north-east. Some 300 yards upstream, a third fault causes dragging in the fluvio-glacials again to about 60° or even 70° north-east.

Immediately west of the last fault comes a group of very large erratics of what are known as the "White Horse type" (described above under "Nangetty Formation"). Not far from the line of this same fault some two and a half miles to the south-east, there is the largest of these giant erratics, the "White Horse" itself, one mile south-east of Mungaterra Homestead. Smaller blocks of the same sort occur elsewhere in the tillite series more or less on this same strike, and it has been suggested that these may be the crest of a barely covered ridge of Pre-Cambrian rocks, but the coincidence of the blocks along this line may be explained perhaps by their stratigraphic position—the strike of the beds and of the faults being almost identical.

The presence of these strike faults both east and west of the " White Horse " was determined already by Woolnough & Somerville (1924, p. 107), from the repetition of small scarps here, which indicated to them a *west* throw of about 50 feet. We were not able to explore this area carefully, but Campbell (1910) recorded *easterly* dips of 36° and 40° just here, which strongly suggests local drags on easterly throwing faults. The termination of the boulder beds south of the " White Horse " Woolnough & Somerville attributed to possible dip faulting, but of this we found no indication.

There is a general convergence of the strike faults from south to north, so that they appear to be progressively fewer, probably also reduced total displacement towards the north. The reason for the reversal of the usual westerly throws along this eastern margin of the Nangetty Glacials, leaving the Nangetty Hills as a low asymmetric horst, is puzzling, but may perhaps be due to differential compaction ; the massive tillites being far less compressible than the adjacent gypseous and saliferous shales of the Holmwood Formation.

As already indicated, the western side of the Nangetty Hills is marked by the Nangetty Fault, which has a remarkable rectilinear trend, and cuts right across our map area. The glacial beds are generally dipping gently to the east (where dips can be detected), but are dragged over to the west in the vicinity of the fault. On the downthrow side there are the Holmwood Shales in the north which are replaced by the upper beds of the Nangetty Formation in the south. In the north there is a fault-line scarp, while in the south it is reversed.

Towards the south, there are additional fault-lines diverging to the south-east from the main fracture, just as on the east side of the hills.

West of the Nangetty Fault there are very poor exposures, and in any case very little work has been done here. No further faulting was identified in the air photographs and dip readings are not clear. The beds seem to be nearly flat or gently undulating, except near the Nangetty Fault itself, where there are westerly dips clearly due to drag. A gentle west dip (about 2 degrees) is probably the explanation of the outcrops of the *Metalegoceras jacksoni* limestone north and south of Macaroni Hill, one and a half miles north-west of Nangetty Homestead. Woolnough & Somerville depicted successively higher beds of the Holmwood Shale appearing west of the Nangetty Glacials, thus implying the existence of regular dips. Of this no confirmation was made.

Finally, about one mile west of Urella Homestead, Woolnough & Somerville identified their *Urella Fault*, a major line, parallel to those described above. Their evidence, briefly, was this : a bore 200 yards north of Urella passed through 497 feet of saliferous " blue clays " (probably Holmwood Shales), while another, half a mile to the west, passed through 507 feet of soft sandstone (" certainly Jurassic " according to Woolnough & Somerville). Since these authors confirm that the general surface outcrops here are almost horizontal, only a fault would account for this displacement. Further bores put down for water by private firms and by the Army in 1943–44 in the Urella-Yarragadee-Mingenew area seem to support this evidence.

On the same trend as the Urella Fault there is a row of important, good fresh-water springs, quite different from the poor saline springs in the Permian. These include Nangade to the north-west, and Eyragulla, south-east of Mingenew. These Woolnough & Somerville quote in further evidence of their fault.

Curiously enough, it is almost unnecessary to introduce all this indirect evidence in favour of the Urella Fault, for the vertical limbs and slickensided surfaces are beautifully exposed at many points along the line. Woolnough & Somerville noted an abrupt break from Permian to Jurassic at a point two miles north-west of Urella Homestead, but standing on the hilltop only one mile south-west of the Homestead, one may observe the steep dips of the fault zone in the down-thrown Jurassic limb extending to the south-south-east across every hilltop as far as the eye can see.

Probably the clearest exposures are on the hilltops two miles south of Yarragadee (off our map area, *see* text-fig. 1) where an abundant Jurassic flora was found. Here the average slickensided fault planes strike N.N.W. and dip 70° west. The beds are much disturbed by drag folds and the structure complicated by smaller cross-faults ; the dips vary from about 20° to 70° west.

The notable difference in detail between this Urella Fault and the clear-cut fractures of the more easterly faults seems to be partly due to differences in lithology and partly to age ; the latter being probably immediately post-Permian and the former being probably Tertiary.

Also probably connected with the Nangetty and Urella Fault lines are the isolated outcrops of marine Permian in some low hills (" Fossil Hill ") two miles east of Mingenew and at Enanty Hill, three miles north-east of Mingenew, two points roughly midway between Urella and Yandanooka (Campbell, 1910, pp. 55–56). These hills rise from the broad alluvial plain of the Lockier River, so that the stratigraphical position of the beds is not clear, and to avoid confusion Woolnough & Somerville (1924, pp. 96–97) called them the " Mingenew Beds."

Special visits were paid to both localities in order to try and shed some light on the general structural problem. At Enanty Hill nearly 400 feet of ferruginous sandstones and grits, with thin shaley and silty bands, dip uniformly 15° N.N.E. Slickensided surfaces are fairly common in the shales, and the hill is cut off fairly sharply on both the west and east, apparently by major faults. Near the top is a highly fossiliferous band of Permian marine fossils, mainly spiriferids and productids (sample 29977).

The southern outcrop, " Fossil Hill " was found to expose a rather similar structure and lithologic sequence, but with more mudstones and siltstones, and near the top of the sequence were four important Permian marine fossil horizons (samples 29908–29). The thickness exposed was about 700 feet and the dip again averaged 15° N.N.E. We identified two important cross-faults trending W.N.W., one in the south and the other in the north of this outcrop ; the latter is partly marked by a large silicified sandstone dyke, as mentioned already by Campbell (1910, p. 55), and by Woolnough & Somerville (1924, p. 97).

It is significant that both these faunas suggest affinities to the higher Permian (Fossil Cliff Formation), and in any case the marine beds here would indicate a very great fault between here and the Nangetty Glacial country to the east. The line on the east is approximately where one would expect the southern extension of the Nangetty Fault, and a throw of over a thousand feet must be considered. The hills seem to be cut off just as sharply on the west, on a line where one would expect the Urella Fault to run. Thus both Enanty and " Fossil " Hills appear to lie between major fracture lines as narrow, distorted fault blocks.

In conclusion, therefore, on the question of structure, we may describe the Irwin Basin as belonging to part of a great series of fault-blocks, each down-thrown to the west and yet gently tilted up along its western edge in an antithetic manner. Thus the basement rocks come close to the surface along the western edge of each block while a fairly thick sequence of the soft overlying Permian cover rocks is preserved towards each eastern margin. Complex gravitational settling and faulting has occurred in these superficial sediments. There appears to be some differential compaction around the more massive glacial facies, possibly disposed over an irregularly eroded Pre-Cambrian surface in the basement, which suggests a small "buried hill" structure in the Nangetty Hills belt. There is, however, no trace of a broad anticline, or, for that matter, of any compressional folding in the Permian at all.

## VI.—GEOLOGICAL HISTORY.

Brief interpretations of the geological history of the area have been given by Woolnough & Somerville (1924), by Woolnough (1937), and by Clarke, Prider and Teichert (1948, p. 173). The following notes are somewhat more detailed. The palaeontological facts bearing on the question of the geological age of this sequence have been discussed in some detail by Teichert (1941, pp. 389–391, 403–404). It was concluded that the *Metalegoceras* horizon corresponded to the late Sakmarian of the Urals and the Fossil Cliff Formation to the early Artinskian. The entire Irwin River sequence may thus be Lower and Middle Permian in age.

As has been pointed out, no Pre-Cambrian occurs *in situ* in the area west of the Darling Fault, and the nature of the sedimentary contact between the Pre-Cambrian and Permian rocks is not seen therefore in the northern part of the basin, but may be followed to the south in the Yandanooka area. There the younger rocks rest with a marked angular unconformity upon the irregularly eroded surface of the Pre-Cambrian (Campbell, 1910, p. 29). However, the alignment of the Pre-Cambrian Brockman Hills (*see* text fig. 1) and the Mullingarra Axis with the Nangetty Fault block (a horst) may suggest that the Pre-Cambrian basement is here not far below the present surface.

In very early Permian times sub-aqueous glacial shales, fluvio-glacial sediments and even continental tillites were deposited, indicating the presence at times of land ice in the area under consideration. This was, of course, part of the great ice-sheet which at that time must have covered much of the Australian continent.

After the deposition of the Nangetty glacials, the claystones and shales of the Holmwood Formation were deposited under rather abnormal conditions. Woolnough (1937, 1938) has advanced the theory that the formation was deposited in a barred basin. He imagines conditions to have been as follows (1938, p. 21) :—

> "The area was occupied by an extensive bight separated almost, but not completely from the open sea, which probably lay to the north or west. The climate was sufficiently arid to cause an inflow current, with concentration of the salts in the water of the basin, but not enough to develop typical redness of the formations. The sediment deposited consisted of a mixture of fine-textured clay, together with a relatively considerable proportion of colloidal ferruginous and calcareous material precipitated from the concentrating sea water. The access of sea water

through the bar openings was sufficient to preclude concentration to the point of deposition of gypsum or salt beds. The abundant gypsum in the upper beds is secondary, not primary in character.

"The waters were maintained at too high a pitch of salinity to permit the colonization of the area by marine organisms, thus accounting for the extraordinary barrenness in fossils, which is so surprising in a series of sediments of this character.

"The nature of the barrier separating the inlet from the ocean is problematical, since its actual existence has never been objectively proved, possibly because it has never been looked for specifically. The peculiarities of the *Gastrioceras* (*Metalegoceras*) bed point to a single catastrophic incident which, if correctly interpreted here, suggests the existence of a low bar, very little above sea level. I visualize the occurrence of a phenomenally persistent onshore wind, piling up the ocean waters on the lee shore until they broke into the basin and temporarily flooded it. By analogy with their modern representative, the pearly *Nautilus*, it may be assumed that the *Gastrioceras* (*Metalegoceras*) were floating forms inhabiting the open ocean. They were driven in enormous numbers into the highly saline waters of the basin, and the entire argosy of them was destroyed immediately and in one single act. Their remains encountered in countless thousands on one horizon, but not in the beds immediately above or below, prove definitely that we are not dealing here with any long-continued sojourn of the cephalopod types in the waters of a sea or bay. After the irruption of the sea water, the bar reasserted itself, and the former conditions of concentration by evaporation supervened. The large influx of normal sea water brought in a temporary accession of iron and lime, which is marked by the more ferruginous bed in which the cephalopod remains are preserved."

This theory accounts for the great scarcity of fossils, but does not explain very satisfactorily the absence of salt deposits in the lower part of the formation : to account for this absence it would be necessary to assume that throughout the early existence of this basin inflow and evaporation of sea-water had been so finely balanced as to result in salinity conditions which precluded the existence of life in the basin, but did not lead to the precipitation of salt. However this may be, it seems certain that the Holmwood Formation was deposited in a basin which did not communicate freely with the open sea.

We cannot agree with the Woolnough hypothesis as to the aridity (which, incidentally, is not related to "red beds"). We have evidence of a *cool climate* associated with the euxinic (Black Sea) conditions ranging to the super-saline (Caspian-type) conditions of a periodically barred basin. The sediments of the Holmwood Formation are rhythmically banded throughout and periodically there occurred an invasion of new marine water with a precipitation of lime muds. Towards the end of the Holmwood time the sea was probably becoming shallower and warmer ; evaporation occurre and salt and gypsum were precipitated. (Certainly the selenite plates in the joint planes are secondary, but the calcium sulphate can only have originated by solution and reprecipitation of material already present in the sediments. Primary bands of gypsum were found.)

On closer examination, it has been found that at least nine or ten recognisable marine invasions occurred ; each brought in varying number of pelagic animals. *Metalegoceras jacksoni* accompanied only one of these.

Others were characterised by other goniatites, nautiloids, the pelagic *Conularia*, and more eurytopic types of gastropod. The brachiopod *Chonetes* is not uncommon, even in the shales themselves near the top of the sequence. The fauna is restricted and dwarfed—suggesting unfavourable, perhaps cold conditions with inadequate foodstuffs.

Septarian nodules of limestone almost all through the sequence suggest precipitation of lime and colloidal clays, possibly in a periodically supersaline environment.

The unfavourable environment was probably accentuated by stagnant conditions on the sea-floor, in which only anaerobic bacteria could exist. The liberation of $H_2S$ under reducing conditions resulted in the development of marcasite or pyrite (and later the secondary alunite and jarosite). At the same time sapropels were preserved, and in certain bands the shales exhibit a greasy texture and dark olive brown colour.

The nature of the original basin is suggested by the regional structure of this part of Western Australia, which appears to consist of a series of major fault blocks, each 10 to 25 miles wide, extending in N.N.W. to N.W. trends. These appear to be highest on the west and depressed on the east. Almost certainly the movements along the faults started *before* the Permian (major Pre-Cambrian trends parallel them), and thus we might suspect that the ancestral fault blocks also controlled the Irwin Basin of deposition in Permian times. This almost land-locked basin lay to the east of a Pre-Cambrian ridge which rises today in the Northampton-Geraldton-Greenough region (where the Pre-Cambrian is now overlain directly by Jurassic). The ridge of Pre-Cambrian S.S.E. of Mingenew (the Mullingarra Axis) may then have been a partly submerged feature of the contemporary basin. The intermittent bar was thus probably not to the west of the present Irwin Basin, but to the north via the southern parts of the North-West Basin.

The existence of a land barrier to the west is suggested by Carroll's heavy mineral analyses of the Coal Measure rocks which show characteristics of the Northampton-Greenough Pre-Cambrian ridge. On the other hand, there is a close lithological correlation with other Permian rocks towards the northwest (Teichert, 1941). (Similar periodically barred basins, with marcasite and sapropelic shales, etc., have now been recognised in similar fault block areas farther south, in the Perth " Sunkland " during Lower Cretaceous and Eocene.) Oceanographic conditions are thus to be compared with those off the Southern California coast today.

A serpulid reef, with a peculiar pelecypod fauna, forms Macaroni Hill, and quite early in this work it seemed likely that there were other such reefs during Holmwood times. Such a one was recently found in the south-east part of the basin. It is significant, perhaps, from the palaeogeographic point of view, that these reefs are situated near the extreme western and eastern parts of the present basin, a factor possibly suggesting a former shallowing in those directions.

Towards the end of Holmwood time a more varied invertebrate life began to find its way into the area, and by Fossil Cliff time rich animal communities were established in places over the sea floor. The predominating sediment was a dark carbonaceous mud which was only sparsely settled by Bryozoa (Fenestellids) and Brachiopoda (mostly *Linoproductus*). Limestone was being deposited in places where life was more plentiful and here were rich associations of Foraminifera, corals, crinoids, Bryozoa, Brachiopoda, Pelecypoda, and Gastropoda, in addition to scattered nautiloids and trilobites.

The presence of this rich and varied invertebrate life seems to indicate a marked warming in the temperature of the sea, which agrees with that noticed at the beginning of Artinskian time elsewhere in Western Australia (Teichert, 1941).

Nevertheless, alternating with the rich fossiliferous bands of the Fossil Cliff Formation, there is still a considerable proportion of sediment dominated by dark colours, gypsum, marcasite and secondary jarosite, indicating that closed basin conditions with stagnant bottom, rich in $H_2S$, periodically recurred. It would seem that the bar was being pretty thoroughly swamped, but that the deeper parts of the basin were still very poorly aerated.

The gradual invasion of well-rounded sands in the High Cliff Formation indicates an almost revolutionary change in conditions, which may correspond with some regional emergence. The sea had now disappeared from the area and the Irwin River Coal Measures were next laid down under lacustrine conditions. About 15 species of plants, all typical members of the Australian *Glossopteris* flora, have been identified from these beds. Many of the coaly lenses appear to be of drift origin, since underclays have not been seen.

Shortly after the formation of the highest coal seams the sea seems to have returned to the area to begin the deposition of the thick Caryngినia Shales. Near the base these alternate with sandstone bands, in which worm tracks, current bedding and ripple-marks all suggest shallow water marine conditions. Only a few pelecypod remains were found in the North and South Irwin, but farther east in Carynginia Gully, a band containing a fairly rich brachiopod fauna seems to correspond to this horizon. The life was however very much the same as that of Fossil Cliff times.

The presence of erratic boulders and pebble bands, most probably dumped from drifting ice, indicates a deterioration of the climate, or at least a lowering of water temperature sufficient to have allowed ice flows to drift into the area. Also suggestive of cooler conditions are the increased angularity of sand grains and freshness of felspars, which was noticed by Carroll to begin high in the Coal Measures and to continue up into the Carynginia Formation.

Higher up in the shales the sandstone bands die out and a simple rhythmic sequence of ferruginous and jarositic shales continues. Just as in the Holmwood Formation, the presence of only partly oxidised ferruginous material and sulphate minerals suggests a return to partly closed and stagnant euxinic conditions.

Non-marine sands and silts eventually replace the marine shales upwards in the Wagina Formation, which finally becomes an almost purely arenaceous facies, except near the top where plant-bearing mudstone and thin lenticular " dirty " coal seams reappear once more.

The general sequence in the Permian of the Irwin Basin : Glacial (tillites)—Marine—Freshwater (coal)—Marine (some erratics)—Freshwater (plant beds), is so similar to that of New South Wales, that a correlation across the continent is rather tempting, as suggested by Teichert (1941) on lithological and general palaeogeographical grounds, and since supported palaeontologically by I. Crespin (1947).

Normal faulting appears to have followed close upon the end of the sedimentation in the Irwin area, and after elevation the uneven surface was reduced to a peneplain. The truncated Permian beds were deeply indurated with the formation of duricrust, chiefly porcellanous in the case of the shales.

This peneplaned and indurated land surface was next transgressed by the basal conglomerates and continental sands of the "Plateau Beds," part of which may perhaps be Jurassic in age. Further faulting occurred during Tertiary times, notably with the development of the Urella and Moonyoonooka Faults and a considerable revival of erosion took place. These structures were partially masked by further planation and sedimentation, partially eolian, which has extended right into Quaternary times.

General erosion of the Irwin Valley began soon after the end of the Permian, but deep excavation of the basin began only after the elevations and revivals of the Tertiary, and the Quaternary climatic oscillations.

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## APPENDIX.

In 1912 Mr. N. L. Prest was privately employed to test the commercial value of the Irwin coal seams and put down bores for that purpose. Further bores were put down by the Public Works Department in 1920-21. The following information, which we believe to be unpublished hitherto, is taken from particulars on maps in the files of the Geological Survey of Western Australia. The positions of the bores are indicated on our map.

*Prest's No.* 1 *Bore*—

| Depth. (feet) | |
|---|---|
| 0— 10 | Alluvium and red loamy soil. |
| 10—148 | Grey to black shales and sandy shales. |
| 148—151 | Hard sandstone. |
| 151—154 | Carbonaceous sandstone. |
| 154—160 | Hard sandstone. |
| 160—161 | Grey sandy shale. |
| 161—167 | Running sand. |
| 167—176 | Carbonaceous shale. |
| 176—177 | Hard sandstone. |
| 177—182 | Carbonaceous shale. |
| 182—210 | Grey sandy shale. |
| 210 | Carbonaceous shale. |
| 211 | Grey sandy shale. |

*Prest's No.* 2 *Bore*—

| Depth. (feet) | |
|---|---|
| 0— 6 | Alluvium. |
| 6— 10 | Red loamy soil. |
| 10— 13 | Grey sandy shale. |
| 13— 20 | Dark grey sandy shale. |
| 20— 44 | Dark grey shale. |
| 44— 80 | Dark grey shale with carbonaceous shale pipings. |
| 80— 86 | Light blue shale. |
| 86—100 | Dark grey shale. |
| 100—101 | Light grey shaley sandstone. |
| 101—110 | Very dark shale. |
| 110—150 | Grey sandy shale. |
| 150—156 | Dark grey shale. |
| 156—164 | Light grey sandy shale. |
| 164—170 | Dark grey sandstone with shaley partings. |
| 170—190 | Carbonaceous shale. |

*Prest's No.* 3 *Bore*—

| Depth. (feet) | |
|---|---|
| 0— 10 | Clay. |
| 10— 21 | Limestone. |
| 21— 24 | Shale. |
| 24— 30 | Very dark grey shale. |
| 30—108 | Sandstone band. |
| 108—110 | Shale. |
| 110—135 | Carbonaceous shale. |
| 135—173 | Black sandy shale. |
| 173—204 | Light sandstone. |
| 204—206 | Black sandy shale. |

*Prest's No.* 4 *Bore*—

| Depth. (feet) | |
|---|---|
| 0— 31 | Ironstone rubble. |
| 31— 52 | Reddish sandstone. |
| 52— 60 | Soft shaley sandstone. |
| 60—143 | Light grey shale. |
| 143—180 | Dark grey shale. |
| 180—181 | White sandy shale. |
| 181—189 | Dark grey shale. |
| 189—191 | Carbonaceous shale. |
| 191 | Dark grey shale. |

*Prest's No.* 5 *Bore*—

| Depth. (feet) | |
|---|---|
| 0— 20 | Alluvium and red clay. |
| 20— 24 | Light grey shale. |
| 24— 58 | Very hard slatey grey shale. |
| 58— 74 | Light grey sandy shale. |
| 74—176 | Grey sandy shale. |

*Prest's No.* 6 *Bore*—

| Depth. (feet) | |
|---|---|
| 0— 5 | Red loamy soil. |
| 5— 19 | Red clay. |
| 19— 24 | Grey shale. |

*P.W.D. Bore No.* 1 (*put down by State in* 1920)—

| Depth. (feet) | |
|---|---|
| 0— 2 | Soil. |
| 2— 18 | Ironstone. |
| 18—170 | Dark shale. |
| 170—202 | Shale with boulders and bands of grit. |
| 202—230 | Dark shale with bands of sandstone. |
| 230—324 | Sandy shale with bands of sandstone. |
| 324—325 | Carbonaceous shale. |
| 325—335 | Sandy shale. |
| 335—341 | Sandstone with shale bands. |
| 341—342 | Sandy shale. |
| 342—343 | Coal. |
| 343—345 | Sandy shale. |
| 345—354 | Grey sandstone. |
| 354—355 | Coal. |
| 355—357 | Sandstone. |
| 357—358·5 | Coal. |
| 358·5—409 | Grey sandy shale. |
| 409—410 | Grey sandstone. |
| 410—411 | Coal. |
| 411—457 | Grey sandy shale with many narrow bands of black carbonaceous shale. |
| 457—458 | Coal. |
| 458—459 | Carbonaceous shale. |
| 459—460 | Grey sandy shale. |
| 460—461 | Coal. |
| 461—491 | Grey sandy shale with pyrite nodules. |
| 491—498 | Grey shale. |
| 498—516 | Dark sandy shale with pyrite nodules. |
| 516—580 | Soft grey sandstone. |
| 580—586 | Sandstone with hard nodules. |
| 586—587·5 | Hard pyritic band. |
| 587·5—605 | Black puggy shale. |
| 605—619 | Fine grained shaley mudstone with small pyrite nodules. |
| 619—670 | Grey shale. |
| 670—674·6 | Hard band. |

*P.W.D. Bore No.* 2 (*put down by State in* 1921)—

| Depth. (feet) | |
|---|---|
| 0— 7 | Ironstone. |
| 7— 10 | Blue clay. |
| 10—298 | Dark shale (5 in. boulder at 205 ft.). |
| 298—340 | Tough shale with small hard bands. |
| 340—390 | Sandy shale. |
| 390—400 | Dark shale. |
| 400—419 | Sandstone. |
| 419—423 | Sandy shale. |
| 423—435 | Blue marl. |
| 435—438 | Sandy shale. |
| 438—439 | Coal. |
| 439—451·5 | Sandy shale. |
| 451·5–457·5 | Coal. |
| 457·5—460 | Sandy shale. |
| 460—461·5 | Coal. |
| 461·5—463 | Dark shale. |
| 463—471 | Sandstone. |
| 471—495 | Sandstone and shale. |
| 495—525 | Sandy shale. |
| 525—537·5 | Coal. |
| 537·5–541·5 | Sandy shale. |
| 541·5–543·5 | Coal. |
| 543·5–557·5 | Sandy shale. |
| 557·5–559·5 | Coal. |
| 559·5—565 | Grit. |
| 565—566 | Coal. |
| 566—572·5 | Shale. |
| 572·5—582 | Shale with narrow coal seams. |
| 582—605 | Sandy shale. |
| 605—681 | Sandstone. |
| 681—723 | Light grey shale. |